

**UTILITY PATENT APPLICATION TRANSMITTAL**  
**(Small Entity)***(Only for new nonprovisional applications under 37 CFR 1.53(b))*Docket No.  
88405.99R077

Total Pages in this Submission

**TO THE ASSISTANT COMMISSIONER FOR PATENTS****Box Patent Application**  
**Washington, D.C. 20231**

Transmitted herewith for filing under 35 U.S.C. 111(a) and 37 C.F.R. 1.53(b) is a new utility patent application for an invention entitled:

**ILLUMINATION DEVICE FOR PROJECTION SYSTEM AND METHOD FOR FABRICATING**

and invented by:

**Bruce W. Smith**If a **CONTINUATION APPLICATION**, check appropriate box and supply the requisite information:☐ Continuation ☐ Divisional ☐ Continuation-in-part (CIP) of prior application No.: \_\_\_\_\_

Which is a:

☐ Continuation ☐ Divisional ☐ Continuation-in-part (CIP) of prior application No.: \_\_\_\_\_

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Enclosed are:

**Application Elements**

1. ☐ Filing fee as calculated and transmitted as described below
2. ☒ Specification having 31 pages and including the following:
  - a. ☒ Descriptive Title of the Invention
  - b. ☒ Cross References to Related Applications *(if applicable)*
  - c. ☐ Statement Regarding Federally-sponsored Research/Development *(if applicable)*
  - d. ☐ Reference to Microfiche Appendix *(if applicable)*
  - e. ☒ Background of the Invention
  - f. ☒ Brief Summary of the Invention
  - g. ☒ Brief Description of the Drawings *(if drawings filed)*
  - h. ☒ Detailed Description
  - i. ☒ Claim(s) as Classified Below
  - j. ☒ Abstract of the Disclosure

# UTILITY PATENT APPLICATION TRANSMITTAL (Small Entity)

(Only for new nonprovisional applications under 37 CFR 1.53(b))

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## Application Elements (Continued)

3. ☒ Drawing(s) (when necessary as prescribed by 35 USC 113)
- a. ☐ Formal      b. ☒ Informal      Number of Sheets 22
4. ☒ Oath or Declaration
- a. ☒ Newly executed (original or copy)      ☐ Unexecuted
- b. ☐ Copy from a prior application (37 CFR 1.63(d)) (for continuation/divisional application only)
- c. ☒ With Power of Attorney      ☐ Without Power of Attorney
- d. ☐ DELETION OF INVENTOR(S)  
Signed statement attached deleting inventor(s) named in the prior application,  
see 37 C.F.R. 1.63(d)(2) and 1.33(b).
5. ☐ Incorporation By Reference (usable if Box 4b is checked)  
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under  
Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby  
incorporated by reference therein.
6. ☐ Computer Program in Microfiche
7. ☐ Genetic Sequence Submission (if applicable, all must be included)
- a. ☐ Paper Copy
- b. ☐ Computer Readable Copy
- c. ☐ Statement Verifying Identical Paper and Computer Readable Copy

## Accompanying Application Parts

8. ☐ Assignment Papers (cover sheet & documents)
9. ☐ 37 CFR 3.73(b) Statement (when there is an assignee)
10. ☐ English Translation Document (if applicable)
11. ☐ Information Disclosure Statement/PTO-1449      ☐ Copies of IDS Citations
12. ☐ Preliminary Amendment
13. ☒ Acknowledgment postcard
14. ☒ Certificate of Mailing
- ☐ First Class      ☒ Express Mail (Specify Label No.): EL407176895US

# UTILITY PATENT APPLICATION TRANSMITTAL (Small Entity)

(Only for new nonprovisional applications under 37 CFR 1.53(b))

Docket No.  
88405.99R077

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## Accompanying Application Parts (Continued)

15. ☐ Certified Copy of Priority Document(s) (if foreign priority is claimed)
16. ☒ Small Entity Statement(s) - Specify Number of Statements Submitted: 1
17. ☐ Additional Enclosures (please identify below):

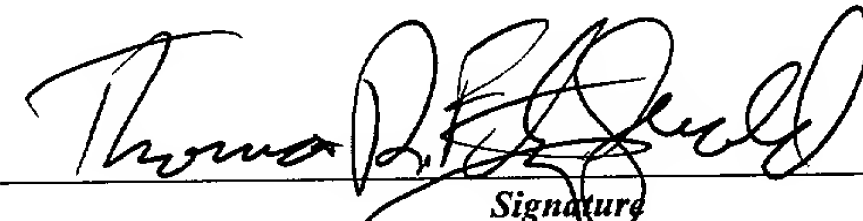
## Fee Calculation and Transmittal

### CLAIMS AS FILED

For	#Filed	#Allowed	#Extra	Rate	Fee
Total Claims	56	- 20 =	36	x \$9.00	\$324.00
Indep. Claims	6	- 3 =	3	x \$39.00	\$117.00
Multiple Dependent Claims (check if applicable) <input type="checkbox"/>					\$0.00
BASIC FEE					\$380.00
OTHER FEE (specify purpose)					\$0.00
TOTAL FILING FEE					\$821.00

- ☒ A check in the amount of **\$641.00** to cover the filing fee is enclosed.
- ☒ The Commissioner is hereby authorized to charge and credit Deposit Account No. **10-0223** as described below. A duplicate copy of this sheet is enclosed.
- ☒ Charge the amount of **\$180.00** as filing fee.
- ☒ Credit any overpayment.
- ☒ Charge any additional filing fees required under 37 C.F.R. 1.16 and 1.17.
- ☐ Charge the issue fee set in 37 C.F.R. 1.18 at the mailing of the Notice of Allowance, pursuant to 37 C.F.R. 1.311(b).

Dated: **October 21, 1999**

  
Signature

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**CERTIFICATE OF MAILING BY "EXPRESS MAIL" (37 CFR 1.10)**Applicant(s): **Bruce W. Smith**

Docket No.

**88405.99R077**

Serial No.

**TBA**

Filing Date

**Herewith**

Examiner

**Unknown**

Group Art Unit

**Unknown**Invention: **ILLUMINATION DEVICE FOR PROJECTION SYSTEM AND METHOD FOR FABRICATING**I hereby certify that this Utility Patent Application Transmittal Letter (Small Entity) (3 pgs)*(Identify type of correspondence)*

is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under

37 CFR 1.10 in an envelope addressed to: The Assistant Commissioner for Patents, Washington, D.C. 20231 on

October 21, 1999*(Date)*Penny R. Turrell*(Typed or Printed Name of Person Mailing Correspondence)*  
*(Signature of Person Mailing Correspondence)*EL407176895US*("Express Mail" Mailing Label Number)***Note: Each paper must have its own certificate of mailing.**

**VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY  
STATUS (37 CFR 1.9(f) AND 1.27 (b)) - INDEPENDENT INVENTOR**

Docket No.  
**88405.99R077**

Serial No.  
**TBA**

Filing Date  
**Herewith**

Patent No.  
**Unknown**

Issue Date  
**Unknown**

Applicant/ **Bruce W. Smith**  
Patentee:

Invention: **ILLUMINATION DEVICE FOR PROJECTION SYSTEM AND METHOD FOR FABRICATING**

As a below named inventor, I hereby declare that I qualify as an independent inventor as defined in 37 CFR 1.9(c) for purposes of paying reduced fees under section 41(a) and (b) of Title 35, United States Code, to the Patent and Trademark Office with regard to the invention entitled above and described in:

- ☒ the specification to be filed herewith.  
☐ the application identified above.  
☐ the patent identified above.

I have not assigned, granted, conveyed or licensed and am under no obligation under contract or law to assign, grant, convey or license, any rights in the invention to any person who could not be classified as an independent inventor under 37 CFR 1.9(c) if that person had made the invention, or to any concern which would not qualify as a small business concern under 37 CFR 1.9(d) or a nonprofit organization under 37 CFR 1.9(e).

Each person, concern or organization to which I have assigned, granted, conveyed, or licensed or am under an obligation under contract or law to assign, grant, convey, or license any rights in the invention is listed below:

- ☒ No such person, concern or organization exists.  
☐ Each such person, concern or organization is listed below.

\*NOTE: Separate verified statements are required from each named person, concern or organization having rights to the invention averring to their status as small entities (37 CFR 1.27)

FULL NAME **Bruce W. Smith**

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I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b))

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

NAME OF INVENTOR Bruce W. Smith

SIGNATURE OF INVENTOR 

DATE: 10/21/99

NAME OF INVENTOR \_\_\_\_\_

SIGNATURE OF INVENTOR \_\_\_\_\_

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DATE: \_\_\_\_\_

10 ILLUMINATION DEVICE FOR PROJECTION SYSTEM  
AND METHOD FOR FABRICATING

Cross-reference to Related Applications

This invention claims the benefit of the priority date of the following U. S. Provisional Application Nos. 60/105,281 filed October 22, 1998 (Attorney Docket #88405.98R231) and 60/119,780, filed February 11, 1999 (Attorney Docket #88405.99R030).

Background of the Invention

20 Optical lithography has been one of the principal driving forces behind the continual improvements in the size and performance of the integrated circuit (IC) since its inception. Feature resolution down to  $0.30\ \mu\text{m}$  is now routine using the 365 nm mercury (Hg) i-line wavelength and optical projection tools operating at numerical apertures above 0.55 with aberration levels below  $0.05\ \lambda$  RMS OPD. The industry is at a point where resolution is limited for current optical lithographic technologies. In order to extend capabilities toward sub- $0.25\ \mu\text{m}$ , modifications in source wavelength, optics, illumination, masking, and process technology are required and are getting very much attention.

However, as devices get smaller, the photomask pattern becomes finer. Fine patterns diffract light and thus detract from imaging the photomask onto the surface of a wafer. FIG. 1a shows what happens when a photomask with a fine pattern 6 having a high frequency (pitch  $2d$  is about several microns), is illuminated through a projection lens system 7. The fine pattern 6 is illuminated along a direction perpendicular to the surface thereof and it diffracts the light that passes through the mask 6. Diffraction rays 3 - 5 caused by the pattern include a zero-th order diffraction ray 5 directed in the same direction as the direction of advancement of the input ray, and higher order diffraction rays such as positive and negative first order diffraction rays 3, 4, for example, directed in directions different from the input ray. Among these diffraction rays, those of particular diffraction orders such as, for example, the zero-th order diffraction ray and positive and negative first order diffraction rays 3, 5, are incident on a pupil 1 of the projection lens system 7. Then, after passing through the pupil 1, these rays are directed to an image plane of the projection lens system, whereby an image of the fine pattern 6 is formed on the image plane. In this type of



5 image formation, the ray components which are contributable to the contrast of the image are higher order diffraction rays. If the frequency of a fine pattern increases, it raises a problem that an optical system does not receive higher order diffraction rays. Therefore, the contrast of the image degrades and, ultimately, the imaging itself becomes unattainable.

10 As will be shown below, some solutions to this problem rely upon shaping the rays of light impinging the photomask in order to provide off-axis illumination to compensate for the lost contrast due to diffraction. These techniques rely upon optical systems for shaping the rays that illuminate the photomask.

In considering potential strategies for sub-0.25  $\mu\text{m}$  lithography, the  
15 identification of purely optical issues is difficult. Historically, the Rayleigh criteria for resolution (R) and depth of focus (DOF) has been utilized to evaluate the performance of a given technology:

$$R = k_1 \lambda / \text{NA}$$

$$\text{DOF} = \pm k_2 \lambda / \text{NA}^2$$

20 where  $k_1$  and  $k_2$  are process dependent factors,  $\lambda$  is wavelength, and NA is numerical aperture. As wavelength is decreased and numerical aperture is increased, resolution capability improves. Considered along with the wavelength-linear and NA-quadratic  
25 loss in focal depth, reasonable estimates can be made for system performance. Innovations in lithography systems, materials and processes that are capable of producing improvements in resolution, focal depth, field size, and process performance are those that are considered most practical.

30 The Hg lamp is a source well suited for photolithography and is relied on almost entirely for production of radiation in the 350-450 nm range. Excimer lasers using argon fluoride (ArF) and krypton fluoride (KrF), which produce radiation at 193 nm and 248 nm, respectively, are also used. DUV lithography at 248 nm is now being implemented into manufacturing operations and may be capable of resolution to  
35 0.18  $\mu\text{m}$

The control of the relative size of the illumination system numerical aperture has historically been used to optimize the performance of a lithographic projection tool. Control of this NA with respect to the projection systems objective lens NA allows for modification of spatial coherence at the mask plane, commonly referred to  
40 partial coherence. This is accomplished through specification of the condenser lens pupil size with respect to the projection lens pupil in a Köhler illumination system. Essentially, this allows for manipulation of the optical processing of diffraction



information. Optimization of the partial coherence of a projection imaging system is conventionally accomplished using full circular illuminator apertures. By controlling the distribution of diffraction information in the objective lens with the illuminator pupil size, maximum image modulation can be obtained. Illumination systems can be further refined by considering variations to full circular illumination apertures. A system where illumination is obliquely incident on the mask at an angle so that the zero-th and first diffraction orders are distributed on alternative sides of the optical axis may allow for improvements. Such an approach is generally referred to as off-axis illumination. The resulting two diffraction orders can be sufficient for imaging. The minimum pitch resolution possible for this oblique condition of partially coherent illumination is  $0.5\lambda/NA$ , one half that possible for conventional illumination. This is accomplished by limiting illumination to two narrow beams, distributed at selected angles. The illumination angle is chosen uniquely for a given wavelength ( $\lambda$ ), numerical aperture (NA), and feature pitch (d) and can be calculated for dense features as  $\sin^{-1}(0.5\lambda/d)$  for  $NA = 0.5\lambda/d$ . The most significant impact of off axis illumination is realized when considering focal depth. In this case, the zero-th and 1st diffraction orders travel an identical path length regardless of the defocus amount. The consequence is a depth of focus that is effectively infinite.

In practice, limiting illumination to allow for one narrow beam or pair of beams leads to zero intensity. Also, imaging is limited to features oriented along one direction in an x-y plane. To overcome this, an annular or ring aperture has been employed that delivers illumination at angles needed with a finite ring width to allow for some finite intensity. The resulting focal depth is less than that for the ideal case, but improvement over a full circular aperture can be achieved. For most integrated circuit application, features are limited to horizontal and vertical orientation, and a four-zone configuration may be more suitable. Here, zones are at diagonal positions oriented 45 degrees to horizontal and vertical mask features. Each beam is off-axis to all mask features, and minimal image degradation exists. Either the annular or the four-zone off-axis system can be optimized for a specific feature size, which would provide non-optimal illumination for all others. For features other than those that are targeted and optimized for, higher frequency components do not overlap, and additional spatial frequency artifacts are introduced. This can lead to a possible degradation of imaging performance.

When considering dense features (1:1 to 1:3 line to space duty ratio), modulation and focal depth improvement can be realized through proper choice of illumination configuration and angle. For true isolated features, however, discrete diffraction orders would not exist; instead a continuous diffraction pattern is produced. Convolution of such a frequency representation with either illumination zones

or annular rings would result in diffraction information distributed over a range of angles. Truly isolated line performance is, therefore, not improved with off-axis illumination. When features are not completely isolated but have low density ( $>1:3$  line to space duty ratio), the condition for optimum illumination will not be optimal for more dense features. Furthermore, the use of off-axis illumination is generally not required for the large pitch values that correspond to low density geometry. As dense and mostly isolated features are considered together in a field, it follows that the impact of off-axis illumination on these features will differ, and a large disparity in dense to isolated feature performance can result.

One approach to generate off-axis illumination is to incorporate a metal aperture plate filter into the fly eye lens assembly of the projection system illuminator providing oblique illumination. A pattern on such a metal plate would have four quadruple openings (zones) with sizing and spacing set to allow diffraction order overlap for specific geometry sizing and duty ratio on the photomask, as disclosed in JP patent Laid-Open (KOKAI) Publication No.4-267515. Such an approach results in a significant loss in intensity available to the mask, lowering throughput and making the approach less than desirable. Additionally, the four circular openings need to be designed specifically for certain mask geometry and pitch and would not improve the performance of other geometry sizes and spacings. Large levels of mask biasing or mask optical proximity correction (OPC), where mask features are pre-distorted to produce desired image characteristics, would be required to allow for use of this approach with a variety of features. Filtering, by limiting its effective area, reduces the effect of the fly eye diffuser on maximizing illumination uniformity. Illumination uniformity may be degraded. This approach also limits the illumination profile to one having holes in a metal plate. That is, the masking metal must remain contiguous. The previous work in this area describes such methods using either two or four openings in the aperture plate: EP0500393, US5305054, US5673103, US5638211, EP0496891, EP0486316, US 37,9252.

Another approach to off-axis illumination using the four-zone configuration, which is disclosed in U.S. Patent No. 5,627,625, is to divide the illumination field of the projection system into beams that can be shaped to distribute off-axis illumination to the photomask. By incorporating the ability to shape off-axis illumination, throughput and flexibility of the exposure source is maintained. Additionally, this approach allows for illumination that combines off-axis and on-axis (conventional) characteristics. By doing so, the improvement to dense features that are targeted with off-axis illumination is less significant than straight off-axis illumination. The performance of less dense features, however, is more optimal because of the more preferred on-axis illumination for these features. The result is a reduction in the

optical proximity effect between dense and isolated features. Optimization is less dependent on feature geometry and more universal illumination conditions can be selected.

5 A problem with this divided illumination approach is that it requires reconfiguration of the illumination system of a projection tool, a task that is not practical on existing tools or systems designed with other illumination systems. Additionally, the use of divided beam illumination limits the fine control of beam shape, size, and position to that which is possible with optical components utilized in the system. Variations in shape, size, position, number of beams, maximum aperture  
10 size, or other feature or lens specific variations to the illumination intensity profile become difficult without significant mechanical modifications. Some variations may not be practical or possible with this approach. This has significantly limited the acceptance or use of this approach in most integrated circuit fabrication operations.

## 15 Summary of the Invention

A shaped illumination approach is described that allows for off-axis illumination of a photomask in a projection exposure tool. It is necessary to control both the off-axis and the on-axis character of the illumination for instance so that  
20 dense line performance can be improved and more isolated line performance can be maintained, i.e., optical proximity effect (hereinafter "OPE") is kept to a minimum. Minimal OPE correction is desired to reduce mask complexity. There is also a desire for a flexible technique that can be incorporated into most existing or future generation projection exposure tools with a minimum amount of illumination system retrofitting. It is important that such an improvement be easily removed to allow a  
25 return to original operation conditions since it is expected that a given projection exposure system would be used for a variety of applications. Such an approach can lead to optimizing illumination conditions, which can be incorporated into an exposure system as a more permanent condition. The invention also provides an improvement that allows for fine adjustment or modification to accommodate mask-  
30 specific or lens-specific characteristics is important as resolution and focal depth requirement are pushed beyond the capability of conventional optical lithography. Maintaining illumination throughput is also critical, as any loss in intensity will result in increased exposure time requirements.

35 The invention provides such a solution. It modifies existing illumination system by adding a masking aperture in the illumination pupil plane, fabricated as an optical component reticle, patterned and dithered into a large number of elements to allow for control of the projected light distribution at the mask plane and inserted at

the condenser lens pupil plane. This masking aperture comprises a translucent substrate and a masking film. The distribution of the intensity through the masking aperture in the illumination pupil plane, is determined to provide optimized illumination. The illumination region or regions exhibit varying intensity, which is accomplished by creating a half-tone pattern via pixelation of the masking film, thereby allowing for maximum variation in illumination beyond the simple binary (clear or opaque) possible with earlier pupil plane filtering approaches.

More specifically, the invention includes an aperture mask for an illumination system to provide controlled on-axis and off-axis illumination. The aperture mask acts as a diffraction element. The aperture mask is divided into an array of elements and each element contains an array of pixels. Each of the elements is constructed with a matrix of pixels. In the preferred embodiment the array of pixels is 8 x 8. The number of elements in the illumination array are generally larger than 3 x 3 and array sizes of 21 x 21 and 51 x 51 are an example, which correspond to 441 and 2601 elements respectively. The elements are patterned in accordance with a selected wavelength of incident light to diffract the incident light into an illumination pattern for illuminating a photomask.

The intensity is modulated by the intensity state of pixels within each element. The highest intensity element has all pixels clear or maximum intensity. Light of suitable wavelength passes through without attenuation. An element with 64 pixels having dark or minimum intensity attenuates or blocks all light. Elements of intensity between none (0%) and all (100%) are created by the state of the pixels in a given element. Random patterns and other patterns between elements may produce artifacts similar to moire patterns. Such artifacts are undesired. I discovered that a dithered pattern using position dependent thresholds produced illumination patterns that had little or no artifacts.

I also discovered that traditional, optical shaping systems such as beam-splitters or diffractive optical elements and my diffraction shaping system can each be improved by adding an illumination aperture. A square illumination aperture shows maximum improvement. It is located at or near the pupil of the illumination system. An aperture with a large, central square opening and an opaque border is inserted at the condenser lens pupil proximate to the fly's eye lens. It can also be designed into the masking aperture. The resulting illumination pattern fills the corners and squares the edges of the illumination pupil and limits the non-optimal frequency spreading character along the x and y axes while optimizing the off-axis illumination angles. The square illumination aperture is especially helpful for imaging features that are oriented along x and y directions in the mask plane. The use of a central obscuration (square and also round shaped) applied in the same location can similarly be achieved

and can lead to performance improvements described hereinafter. Furthermore, any combination of off-axis illumination with a square pupil or obscuration has potential to improve performance for geometry oriented in the x-y direction. This can include, but is not limited to, round zones, elliptical zones, square zones, and annular slots (that is an annular ring masked off on x and y axis to form arc-shaped zones).

### Brief Description of the Drawings

**Figure 1a** 1 is a schematic view of an illumination system for a photomask.

**Figure 1b** shows the zero-th and first positive and first negative diffraction rays.

**Figure 2** is a drawing showing diffraction orders (first and zero) for 130 nm x-oriented features using four-zone illumination, plotted in the frequency plane of the objective lens. Center sigma is 0.68 and radius sigma is 0.13, chosen to accommodate feature pitch values from 260 to 455 nm.

**Figure 3** is a drawing of the continuous tone intensity distribution for a masking aperture based on four distributed-intensity zones.

**Figure 4** is a plot of the x-y distribution of dithered bilevel masking cells for an illumination aperture consisting of four circular normal distributed-intensity zones placed at diagonal positions corresponding to off-axis illumination for geometry oriented in horizontal and vertical directions.

**Figure 5** is a three dimensional plot of the x-y distribution shown in Figure 4.

**Figure 6** is a drawing of surface contours of the continuous tone intensity distribution for a masking aperture based on two distributed-intensity zones where the maximum off-axis angle is limited to one direction.

**Figure 7** is a plot of the x-y distribution of dithered, bilevel masking cells for an illumination aperture consisting of four elliptical normal distributed-intensity zones placed at diagonal positions corresponding to off-axis illumination for geometry oriented in horizontal and vertical directions.

**Figure 8** is a contour plot of the x-y distribution shown in Figure 7.



Figure 9 is a three dimensional plot of the x-y distribution for an illumination aperture consisting of four stepped square distributed-intensity zones placed at diagonal positions corresponding to off-axis illumination for geometry oriented in horizontal and vertical directions.

Figure 10 is a contour plot of the x-y distribution for an illumination aperture consisting of four stepped square distributed-intensity zones, as described for Figure 9.

Figure 11 is a plot of the x-y distribution of dithered, bilevel masking cells for an illumination aperture consisting of four elliptical normal distributed-intensity zones, as described for Figure 9.

Figure 12 is a schematic representation of the bilevel representation of 65 gray levels using the ordered dithering algorithm.

Figure 13 is a graph showing normalized aerial image log-slope (NILS) vs focus for 130 nm features using four-zone illumination,  $\sigma_c=0.68$  and  $\sigma_r=0.20$ .

Figure 14 is a graph showing normalized aerial image log-slope (NILS) vs. focus for 130 nm features using distributed-intensity four-zone illumination ( $\sigma_c=0.68$  and  $\sigma_r=0.30$ ) and a circular hard stop ( $\sigma=0.8$ ).

Figure 15a is a graph showing normalized image log slope (NILS) vs. focus for 130 nm features using the illumination shown in Figure 19.

Figure 15b is a graph showing normalized image log slope (NILS) vs. focus for 130 nm features using the illumination shown in Figure 23.

Figure 15c is a graph showing normalized image log slope (NILS) vs. focus for annular ring illumination of 150 nm features using 248 nm wavelength and 0.63 NA, with duty ration of 1:1.5 to 1:5.

Figure 15d is a graph showing normalized image log slope (NILS) vs. focus for square ring illumination of 150 nm features using 248 nm wavelength and 0.63 NA, with duty ration of 1:1.5 to 1:5.

- 5 drawing of the continuous tone intensity distribution for a masking aperture based on four circular zones and a background with an intensity value of 0.25.

**Figure 16** is a plot of the normalized image log slope, showing influence of a circular four-zone ( $\sigma_c=0.7$  and  $\sigma_r=0.2$  on a zero intensity field) with 0.1 waves of primary  
10 aberrations: astigmatism, tilt, spherical, and coma, through focus for a 130 nm features imaged with a 193nm imaging system using a numerical aperture of 0.6.

**Figure 17** is a plot of the normalized image log slope, using the bi-level  
15 representation of the distributed-intensity illumination described for this invention.

**Figure 18** is a contour plot of circular gaussian zones used to optimize energy distribution in the pupil, where energy is concentrated in the center of the pupil and at  
20 off-axis angles.

**Figure 19** is a three dimensional plot of circular gaussian zones and a square limiting zone used to limit the on-axis illumination component while retaining off-axis zone energy.

**Figure 20** is a perspective view of a beamsplitter illumination system with a square  
25 aperture mask inserted in its pupil.

**Figure 21** shows how a square central obscuration can be included in an aperture to reduce the on-axis character of illumination and improve the performance of dense  
30 features.

**Figure 22** shows the square ring, off-axis source which delivers optimal off-axis illumination for dense features while providing on-axis illumination for more isolated  
35 features.

**Figure 23** shows how the square ring approach can be combined with the gaussian four-zone approach to emphasize corner zone effects.



**Figure 24** is a contour plot of a combined annular and gaussian four-zone aperture to improve the off-axis character of annular illumination.

- 5 **Figure 25** is an illumination system using diffractive optical elements and a square aperture.

**Figure 26** is a 51 x 51 element array of a dithered half tone pattern.

10 Detailed Description of the Invention

For given ranges of feature types and/or sizes (types being lines, spaces, contacts, and dense or isolated combinations of these) exposure conditions are optimized by determining the average off-axis angle to accommodate all features.

- 15 The distribution of off-axis angles is then determined based on the range of feature sizes of interest. As the range of feature sizes increases, the condition of off-axis illumination approaches a limit equivalent to the on-axis condition. Most commonly, duty ratios for a given feature size may range from 1:1 to 1:6 line:space ratio. The spread of off-axis illumination angles is accomplished by shaping zones (for the two or more zone, including four-zone) or rings (for the annular) to produce continuous intensity distributions.

- 20 As an example of the design considerations, 130 nm features are considered using a 193nm exposure wavelength and a 0.60 objective lens numerical aperture. Duty ratios from 1:1 to 1: 6 are included. Features are considered dense with a duty ratio less than 1:3. Table 1 shows the pitch values (p) for these dense features, along with the required axis center sigma and four-zone center sigma ( $\sigma_c$ ) values for optimum off-axis illumination. Center sigma values on axis are determined as  $\lambda/(2p \cdot NA)$ , as shown in Figure 1. Since diffraction order placement is determined by the projection of the four-zone onto the x or y axis, the center four-zone sigma values are larger by a  $(2)^{1/2}$  factor.

- 25 In order to design an off-axis illumination configuration that can accommodate and enhance the range of pitch values in Table 1, zone position and radius values must be chosen so that some amount of order overlap occurs for each case. This can be accomplished if the four-zone center  $\sigma_c$  and the radius  $\sigma_r$  values are set as follows:

$$\sigma_c = \text{SQRT}(2) \cdot (0.61 + 0.35) / 2 = 0.68$$

$$\sigma_r > (0.61-0.35)/2 = 0.13$$

These choices for zone center and radius values correspond to the situation where zero and first diffraction orders begin to overlap for the extreme pitch values of 260 and 455 nm, as shown in Figure 2. The  $(2)^{1/2}$  term does not factor into determination of  $\sigma_r$  values since the zone radius is projected directly onto the axes. The extent of order overlap for these extreme pitch values is, however, mostly ineffectual, and larger  $\sigma_r$  values are required to influence performance. A  $\sigma_r$  value of 0.20 allows for significant order overlap (~20%) and is a more practical starting value for further optimization.

When imaging of both dense and isolated features, illumination that resembles both the strong four-zone and the conventional on-axis illumination is desirable. This can lead, for instance, to the four-zone illumination design where circular zones are replaced with continuous tone zones, as shown in Figure 3.

**Table 1.** Pitch and sigma values for 130 nm features and 1:1 to 1:2.5 duty ratios.

Duty	Pitch (nm)	axis sigma	four-zone sigma
1:1	260	0.61	0.87
1:1.5	325	0.50	0.71
1:2	390	0.42	0.59
1:2.5	455	0.35	0.49

The masking aperture of this invention is a bilevel representation of the desired intensity distribution in the illuminator. It is desired to resemble a near continuously varying transition from open to opaque areas. To achieve this result, the illumination pattern is divided into a large number of elements and each element is a matrix of pixels. Dithering or pixelation of the continuous distribution of intensity is used for translation to the binary or bilevel masking aperture. The element array is large, consisting of, for instance, 5 x 5, 7 x 7, 9 x 9, 11 x 11, 21 x 21 or 51 x 51 elements, but not limited to these cases. The illumination profile is divided into such an element array. Individual masking pixels are small, on the order of 10 to 100  $\mu\text{m}$ , and are either translucent or opaque. Their size is dependent on the size of the physical masking aperture. The continuous tone nature of the illumination intensity profile is translated by controlling the spatial density of the bilevel display states on the masking aperture. Several decision rules may be implemented to produce the output distribution on the masking aperture. A fixed threshold technique is simplest in form, but an ordered dithering approach may be used to most effectively translate a continuous tone intensity profile into a bilevel masking aperture representation.

Intensity values are compared to a position-dependent set of threshold values, contained in a  $n \times n$  dither matrix. A set of selection rules repeats the dither matrix in a checkerboard arrangement over the illumination field. One key to this approach is the generation of a bilevel representation of the continuous tone image with the minimal amount of low spatial frequency noise. In other words, the occurrence of texture, granularity, or other artifacts is reduced to a minimum, allowing for the critical control of illumination uniformity demanded in projection exposure tools.

The resulting bilevel representation of the continuous tone off-axis and/or on-axis illumination profile is then suitable for recording into a photo-sensitive or electron beam-sensitive resist material through use of mask pattern generator. Other approaches might use lithographic techniques common to lithographic or printing technologies. Such a resist material, when coated over an opaque film on translucent substrate, can allow for pattern delineation and creation of the masking aperture.

In the present invention, the existing intensity distribution at the pupil plane of an illumination system for a projection exposure tool is modified through use of a bilevel masking aperture containing a masking cell representation of a continuous tone intensity distribution. Figures 4 and 5 show such distributions where four distributed-intensity zones allow for off-axis and on-axis illumination of a photomask that contains geometry oriented in horizontal and vertical directions only. A maximum circular dimension is defined by a limiting zone, designed to limit the maximum off-axis angle projected onto the mask. This is used to balance the off-axis illumination provided to the mask with the degree of coherency of the on-axis illumination. Smaller geometry requires higher levels of on-axis partial coherence, leading to larger limiting zones. The extent of the zone will generally correspond to positions near or beyond the maximum zone or angular position for the off-axis illumination, generally in, but not limited to, the range from 0.5 to 1.0. The intensity at any position located beyond this limiting zone is set to zero. The shape of this limiting zone is not necessarily circular, and selection of the shape will depend on the extent of feature orientation at the mask. Features constrained to one orientation only require limitation of off-axis illumination in one direction, resulting in assigning a value of zero to any element beyond the required x or y value corresponding to the limiting angle, as shown in Figure 6. This allows for maximum energy at angles with the desired range and can lead to improved imaging and throughput performance. Features constrained to two orientations only require that the aperture limit off-axis illumination angles in two orthogonal directions, leading to a non-circular or square two dimensional character of the limiting zone as shown in Figure 19. The invention allows for this tailoring of the illumination.

If the existing illumination intensity distribution at the pupil plane of the illumination system is not uniform, the non-uniformity at the plane can be deconvolved in accordance with the invention to result in a masking aperture that also incorporates compensation for non-uniformity. For example, many steppers provide a pupil that is guaranteed uniform ( $\pm 1\%$ ) for only 80% of its full opening. At 85% open, the uniformity of illumination may vary up to  $\pm 10\%$  or more. With the invention, the non-uniformity may be canceled or reduced to an acceptable level.

The overlapping of the continuous intensity regions in the center of the illumination field produces the on-axis character required for less dense features. The central intensity is generally greater than 0% and is commonly in the 10 to 50 % range.

Illumination zones within the masking aperture control the illumination to mask and are designed to produce optimal off-axis, on-axis, or combined illumination. This invention allows for an infinite variety and number of such zones. Some are most desirable.

Zones may be circular, elliptical, 45 degree elliptical (that is, elliptical but oriented with axes at angles of 45 degrees and 135 degrees), square, or other shapes dependent on the desired distribution of diffraction information to match mask geometry requirements or specific lens behavior. The distribution of the energy in these zones or rings may be stepped, Gaussian, Lorentzian, or other similar shape. The kurtosis of gaussian distributions may be normal (mesokurtic), narrow (leptokurtic), or flat-topped (platykurtic), or combinations of these among zones. Skewness, or departure from symmetry of the distribution may be utilized for differential weighting of certain feature sizes. Circular symmetry may be best suited for most general cases and elliptical distributions can be utilized to accommodate x-y nonuniformities of the photomask or imparted by the projection lens (a result for instance of astigmatic or comatic aberration). Figures 7 and 8 show four elliptical normal distributed-intensity zones placed at diagonal positions corresponding to off-axis illumination for geometry oriented in horizontal and vertical directions. Figure 18 shows how rotated elliptical gaussian zones can offer improvements in intensity distribution for x and y oriented geometry by concentrating some energy in the center of the pupil and the remaining energy distributed at four-zone angles. Here, rotation of the zone axis allows for a symmetrical distribution. In this case, energy on the x/y axes is limited, reducing the non-optimal, on-axis illumination of targeted dense features. An increase in the efficiency of zero and first diffraction order overlap can result from such an illumination distribution.

For imaging of geometry in two directions only (x and y only for instance), there is only a need to spread diffraction order information in the direction of

geometry. By limiting zone intensity distribution to x and y directions, resulting in continuous intensity or stepped-square shaped zones, maximum off-axis illumination is maintained up to the maximum angle allowed by the zone dimensions. Beyond these angles, the degree of off-axis illumination is limited and can be tailored more specifically for the x and y oriented geometry. Figure 9 and 10 shows how stepped-square zones are implemented in an illumination profile. Figure 11 shows how this is translated into the bi-level representation.

A square or rectangular shaped obscuration (or an inner limiting zone) emphasizes the off-axis illumination for feature pitch values whose frequency distribution falls beyond the chosen value (greater than  $\lambda/(w \cdot NA)$  where  $w$  is the full width obscuration value between 0 and 2). This is shown in Figure 21 for a gaussian off axis distribution where the obscuration is 30% of the full aperture width. Combining a square outer limiting zone and a square obscuration, an optimal condition of off axis illumination exists also. For features oriented in one direction only, only two zones are needed on an axis opposite to the feature direction. These zones can be slots or rectangles since spreading of energy in the direction of feature orientation is of no consequence to imaging performance and increases throughput. With two dimensional geometry, four slots are needed in x and y direction, resulting in a square ring, as shown in Figure 22. This ring can also be considered as the combination of a square limiting zone and square obscuration. This rectangular ring source distribution can deliver off-axis illumination for features to  $0.25\lambda/NA$ , depending on the choice of the limiting outer square zone. This square ring source distribution can also be combined with other off axis approaches, such as a gaussian four-zone design. Figure 23 shows how a square ring source distribution is added to a gaussian four-zone design to produce results that are common to both approaches (that is better performance for more dense features out to  $0.25\lambda/NA$  and adequate through focus and through pitch imaging performance).

Other combinations of source distributions are possible. Figure 24 shows how an annular ring is combined with a gaussian four-zone design to emphasize the performance of more dense features than possible with the annular distribution alone. This approach can increase the off-axis character of the annulus and reduce the non-optimal on-axis character.

The masking aperture varies the intensity of the transmitted light at any element by modulating the state of pixels in each element. The highest intensity element has all pixels on or at maximum intensity. Light of suitable wavelength passes through without attenuation. In a preferred embodiment as shown in Figure 12, an element with 64 pixels at a minimum intensity attenuates or blocks all light.

Pixels of intensity between none and all are created by the number of pixels in a given element.

A masking aperture with a bilevel representation of such an illumination distribution is created by dithering the continuous tone images. Random techniques or fixed threshold techniques can be used. These fixed threshold techniques are based on decision rules where any intensity value greater than a threshold value (T) results in a transparent masking cell and a value less than T results in an opaque masking cell. The result is generally a high degree on banding in the bilevel representation. A slight improvement over this method is to replace T with equally distributed random numbers over the range 0 to S with a new random number generated for each intensity value. Less banding results but signal to noise is low. A superior approach to the dithered representation is possible by comparing image intensity values to position dependent thresholds contained in an  $n \times n$  dither matrix,  $D^n$ . For a  $D^n$  matrix, a matrix element  $D^n_{i,j}$  is chosen based on a rule set that causes the dither matrix to be repeated in a checkerboard fashion over the entire image with minimum low spatial frequency noise. The proper choice of the dither matrix results in minimum texture or artifacts and maximum uniformity in intensity. In general, the optimum dither matrix is represented by the recursion relationship:

$$D^n = \begin{vmatrix} 4D^{n/2} + D_{00}^2 U^{n/2} & 4D^{n/2} + D_{01}^2 U^{n/2} \\ 4D^{n/2} + D_{10}^2 U^{n/2} & 4D^{n/2} + D_{11}^2 U^{n/2} \end{vmatrix}$$

where:

$$U^n = \begin{vmatrix} 1 & 1 & \dots & 1 \\ 1 & & & \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ 1 & & & \end{vmatrix}$$



To produce an 8x8 matrix to satisfy these optimization criteria, D8 becomes:

$$D^8 = \begin{vmatrix} 0 & 32 & 8 & 40 & 2 & 34 & 10 & 42 \\ 48 & 16 & 56 & 24 & 50 & 18 & 58 & 26 \\ 12 & 44 & 4 & 36 & 14 & 46 & 6 & 38 \\ 60 & 28 & 52 & 20 & 62 & 30 & 54 & 22 \\ 3 & 35 & 11 & 43 & 1 & 33 & 9 & 41 \\ 51 & 19 & 59 & 27 & 49 & 17 & 57 & 25 \\ 15 & 47 & 7 & 39 & 13 & 45 & 5 & 37 \\ 63 & 31 & 55 & 23 & 61 & 29 & 53 & 21 \end{vmatrix}$$

- 10 To utilize this dithering matrix, for example, a continuous tone element intensity distribution is divided into 64 levels. The lowest intensity level places a pixel in the masking element at the zero position. An intensity value of 50% places pixels in the first 31 positions, and so forth. Figure 12 schematically depicts the bilevel representation of 65 gray levels using the ordered dithering algorithm. Figure 26 shows how this approach is used in a 51 x 51 element array. Other possibilities, such as 2-level, 4-level, 16-level, and so forth, are solved for in a similar manner.

The performance improvement for 130 nm features using a 193nm wavelength and 0.60 lens numerical aperture is described using a normalized aerial image log-slope NILS metric (normalized to the feature size). This is the log of the slope of the intensity image (or aerial image). Figures 13 and 14 show NILS plotted against focus position for circular zone and a bi-level representation of distributed-intensity zone off-axis illumination where the central intensity is 26%. The ratios are the line to space size ratio, or duty ratio. The falloff of NILS across all feature duty ratios matches more closely with increasing amounts of defocus for the distributed-intensity zone illumination compared to the circular zone condition. The resulting impact on lithographic imaging is a reduction in the dense to isolated line proximity effect. Figure 15a shows the imaging improvement achieved with the square limiting zone using the illumination profile of Figure 19. Figure 15b shows the further improvement using the hybrid design of Figure 23. Figures 15 a/d show a comparison of the square ring of Figure 22 with an annular (circular) ring for a 248nm



wavelength, 0.63NA & 150nm features at 1:1.5 duty ratio to 1:5 duty ratio. Figure 15c shows the performance for an annular or circular ring and Figure 15d shows the performance for the square ring. Illuminator dimensions are identical, only the shape differs. No circular or annular ring can match the performance of the square ring.

The amount of total intensity allowed to pass through a masking aperture will determine its acceptability in situations where exposure throughput is a concern, such as with the fabrication of integrated circuit devices. Table 2 is a comparison of the throughput efficiency of several variations of the distributed-intensity four-zone approach, measured relative to conventional illumination with a  $\sigma$  of 0.7 and a strong circular zone approach, where off-axis illumination is provided by four circular zones on a zero transmission field. The worst case throughput is for the circular zone four-zone design, where the total intensity through the pupil is 27% of that for conventional illumination with  $\sigma=0.7$ . The distributed-intensity four-zone approach with a  $0.7\sigma$  circular hard stop leads to 83% throughput and the same design with a  $0.7$  half-width square hard stop results in 85% throughput. If the square limiting zone is increased in size to  $0.8$  half-width, the throughput increases to 93% and imaging performance remains comparable to the circular hard stop. This efficiency comes about because of the amount of energy allowed at the corners of the square pupil, where the diagonal approaches the full extent of the condenser lens pupil, or a  $\sigma$  value near 1.0. Comparison of intensity throughput is an important one as illumination modification is considered. If the illumination system of an exposure tool can allow full value,  $\sigma = 1$  operation, this square hard stop variation of the distributed-intensity four-zone can lead to minimal losses.

**Table 2**

Illumination approach	Relative Intensity
Conventional, $0.7 \sigma$	1.00
Circular four-zone $0.68\sigma_c$ , $0.2\sigma_r$ , $0.8\sigma$ stop, 0% field	0.27
Circular four-zone, $0.68\sigma_c$ , $0.2\sigma_r$ , $0.8\sigma$ stop, 25% field	0.52
Distributed-intensity four-zone, $0.68\sigma_c$ , $0.3\sigma_r$ , $0.7\sigma$ circular stop	0.83
Distributed-intensity four-zone, $0.68\sigma_c$ , $0.3\sigma_r$ , $0.7\sigma$ square stop	0.85
Distributed-intensity four-zone , $0.68\sigma_c$ , $0.3\sigma_r$ , $0.8\sigma$ square stop	0.93

For on-axis conventional illumination, lens aberrations are evaluated assuming full use of a lens pupil. With off-axis illumination, diffraction information is distributed selectively over the lens pupil, influencing the impact of aberrations on imaging. In general, astigmatic effects can worsen while spherical aberration and defocus effects can be improved. Coma induced image placement can be further

aggravated with OAI unless rebalanced with tilt. Figure 14 shows how the normalized image log slope is impacted for circular four-zone ( $\sigma_c=0.7$  and  $\sigma_r=0.2$  on a zero intensity field) with 0.1 waves of primary aberrations: astigmatism, tilt, spherical, and coma, through focus for a 130 nm features imaged with a 193nm imaging system, using a numerical aperture of 0.6. Although the effects of spherical aberration are minimal, the loss in NILS for astigmatism, tilt, and coma are significant. Figure 17 shows the same imaging process using the bi-level representation of the distributed-intensity four-zone illumination described in this invention. Similar results are obtained using dithered intensity circular, stepped square, and 45 degree elliptical zones. Here it can be seen that the influences of astigmatism and tilt are reduced at zero defocus values and at larger defocus values (both positive and negative) the influences of all aberrations are reduced substantially, as compared to the case shown in Figure 16.

Implementation of the invention into existing illumination systems is accomplished via access to the illumination optical system. In one embodiment, pixilated half-tone illumination files are transferred lithographically onto a transparent substrate, such as fused silica, coated with a suitably opaque masking layer, such as chromium. A photoresist film coated over the metal coated transparent substrate is exposed using optical, electron beam, or other methods by translating the bi-level illumination representation into a suitable machine-readable format. Photoresist development and subsequent etching of the underlying masking film allows transfer of the pattern to the masking aperture. An anti-reflective layer can be coated over the masking film prior to photoresist coating, exposure, and processing to reduce reflection, stray light, and flare effects in the illumination field of the exposure tool. An anti-reflective layer can be coated over the patterned aperture to match reflectances over the entire illumination field. Alignment of apertures is made possible by incorporating alignment fiducials on the masking apertures and on an aperture holders used to mount the invention into the exposure tool illumination system. Apertures can be inserted into as pupil plane of the illumination system.

Those skilled in the art will understand that a number of the new results achieved with the above-described aperture mask may also be achieved with a traditional beamsplitter illumination system. For example, consider an illumination system such as the one shown and described in U. S. Patent No. 5,627,625. When an aperture mask 60 with a large, central square opening 64 and an opaque border 62 is inserted proximate to the fly's eye or in the lens pupil 19, the four beams from the beam splitter 16 generate contour and three dimensional plots similar to Figures 18 and 19. The beams fill the corners of the illumination pupil and limit the non-optimal frequency spreading character along the x and y axes while optimizing the off-axis

illumination angles. The new results can also be achieved with an illumination system using diffractive optical elements (DOEs) to shape the illumination profile. An example of this illumination shaping method is described, for instance, in U.S. Patent No. 5,926,257 (Canon) and U.S. Patent No. 5,631,721 (SVGL). Figure 25 shows how an aperture (60) with a large, central square opening (64) and an opaque border (62) is inserted proximate to the beam shaping optical system (2). This can allow for shaping with a square limiting zone. Additionally, the beam shaping optical system using diffractive optical elements can be tailored to produce similar results. That is especially helpful for imaging features that are oriented along x and y directions in the mask plane. The use of a central obscuration (square and also round shaped) can similarly be achieved and can lead to performance improvements described here. Furthermore, any combination of off-axis illumination with a square aperture or obscuration has potential to improve performance for geometry oriented in the x-y direction. This can include, but is not limited to, round zones, elliptical zones, square zones, and annular slots (that is an annular ring masked off on x and y axis to form arc-shaped zones).

The masking aperture described above may be used alone or in combination with prior art techniques and apparatus. For example, the masking aperture of the invention may be combined with the four hole metal mask described in JP patent Laid-Open (KOKAI) Publication No.4-267515 and discussed in the background of U.S. Patent No. 5,627,625.

Those skilled in the art will understand that the new results achieved with elliptical, 45 degree elliptical, square rings, and square shaped zones may also be achieved with alternative approaches, including the beamsplitter approach. This could be accomplished for example with the illumination system shown in Figure 20 (and described in U.S. Patent No. 5,627,625) by shaping divided beams into elliptical, 45 degree elliptical, and square shapes in the beamsplitter unit 16 and superposing them using a prism unit 17. Gaussian or similar shaped energy distribution is possible.

Those skilled in the art will also understand that the new results achieved with elliptical, 45 degree elliptical, square rings, and square shaped zone may also be achieved with diffractive optical element approaches to beam shaping, such as that described in U.S. Patent No. 5,926,257 and U. S. Patent No. 5,631,721 by tailoring the diffractive optical elements to exhibit these characteristics. The micro-diffractive optical elements within the beam-shaping optical system (2) in Figure 25 are manipulated to allow for the required shaping. It is well known that diffractive optical elements (DOEs) and holographic optical elements (HOEs) can allow for efficient manipulation of arbitrary wavefronts with more flexibility and reduced

fabrication requirements compared to conventional refractive optics (see for instance Z. Yang and K. Rosenbruch, SPIE Vol. 1354, (1990), 323). One DOE or HOE or the combination of two or more DOEs or HOEs allow for the design flexibility needed to achieve the desired results, as demonstrated for instance in U.S. Patent No. 5,926,257  
5 and in SPIE Vol. 1354, (1990), 323.

The present invention is described above but it is to be understood that it is not limited to these descriptive examples. The numerical values, number of zones, shapes, and limiting zones may be changed to accommodate specific conditions of masking, aberration, feature orientation, duty ratio requirements, lens parameters,  
10 initial illumination non-uniformities, and the like as required to achieve high integrated circuit pattern resolution. Results can also be obtained by controlling illumination at any Fourier Transform plane in the illumination system.

What is Claimed:

1. A masking aperture for an illumination system to provide controlled  
5 illumination of a photomask with two dimensional features comprising:  
a translucent substrate;  
a half-tone dithered image on the substrate, said half-tone dithered image  
comprising an array of pixels for generating a continuous illumination intensity  
pattern on the photomask with illumination intensity at any location controlled by the  
10 half-tone dithered image.
2. The masking aperture of claim 1 wherein each pixel is a clear or opaque type,  
said clear and opaque pixels for respectively passing and blocking incident light,  
wherein the number, size, and type of the pixels are chosen in accordance with:  
15 (a) the wavelength of light used to illuminate the photomask, and  
(b) the size and shape of the features of the photomask,
3. The masking aperture of claim 1 wherein the half-tone dithered image  
comprises an array of diffraction elements and each diffraction element is a dithered  
20 image of clear or opaque pixels.
4. The masking aperture of claim 3 wherein each diffraction element comprises  
an  $n \times n$  dithered matrix of pixels, the intensity of each element is defined by the  
number and type of pixels in its dithered matrix and wherein the pixels in each matrix  
25 are dithered to avoid artifacts.
5. The masking aperture of claim 3 wherein the relative intensity of each element  
is defined by a recursion relationship where:

30

$$D^n = \begin{vmatrix} 4D^{n/2} + D_{00}^2 U^{n/2} & 4D^{n/2} + D_{01}^2 U^{n/2} \\ 4D^{n/2} + D_{10}^2 U^{n/2} & 4D^{n/2} + D_{11}^2 U^{n/2} \end{vmatrix}$$

35 where:

where:

$$U^n = \begin{vmatrix} 1 & 1 & \dots & 1 \\ 1 & & & \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ 1 & & & \end{vmatrix}$$

- 5 6. The masking aperture of claim 5 wherein the matrix of pixels of each element comprises an 8 x 8 matrix and the relative intensity, D8, comprises :

$$D^8 = \begin{vmatrix} 0 & 32 & 8 & 40 & 2 & 34 & 10 & 42 \\ 48 & 16 & 56 & 24 & 50 & 18 & 58 & 26 \\ 12 & 44 & 4 & 36 & 14 & 46 & 6 & 38 \\ 60 & 28 & 52 & 20 & 62 & 30 & 54 & 22 \\ 3 & 35 & 11 & 43 & 1 & 33 & 9 & 41 \\ 51 & 19 & 59 & 27 & 49 & 17 & 57 & 25 \\ 15 & 47 & 7 & 39 & 13 & 45 & 5 & 37 \\ 63 & 31 & 55 & 23 & 61 & 29 & 53 & 21 \end{vmatrix}$$

- 10 7. The masking aperture of claim 4 wherein the matrix of the diffracting elements is selected from the group consisting of 2 x 2, 4 x 4, 8 x 8, 16 x 16, 32 x 32 and 64 x 65.
8. The masking aperture of claim 1 wherein the elements generate one or more zones of controlled intensity.
- 15 9. The masking aperture of claim 8 wherein the zones are symmetrical about the center of the masking aperture.
10. The masking aperture of claim 9 wherein the zones have one shape selected from the group consisting of circles, squares, rectangles, and ellipses, rings, circular rings, square rings, or combinations thereof.
- 20 rings, square rings, or combinations thereof.
11. The masking aperture of claim 10 wherein the selected shape is a stepped square.
- 25 12. The masking aperture of claim 10 wherein the selected shape is an ellipse and the major axis of each ellipse is aligned at a 45-degree angle with respect to the center of the masking aperture.

13. The masking aperture of claim 1 comprising one or more zones arranged symmetrical about the center of the masking aperture.
- 5 14. The masking aperture of claim 1 comprising one or more zones arranged asymmetrical about the center of the masking aperture.
15. A masking aperture for an illumination system to provide controlled illumination of a photomask with two dimensional features, comprising:
- 10 a translucent substrate;
- an array of diffraction elements on the substrate and each diffraction element comprising a half-tone dithered image of clear and opaque pixels;
- each half-tone image comprising an array of pixels, each pixel of a clear or opaque type for respectively passing or blocking incident light, wherein the number,
- 15 size, and type of the pixels are chosen in accordance with:
- (a) the wavelength of light used to illuminate the photomask, and
- (b) the size and shape of the features of the photomask, for generating a continuous illumination intensity pattern on the photomask with illumination intensity at any location controlled by the half-tone dithered image.
- 20 16. The masking aperture of claim 8 comprising a zone with a square ring.
17. The masking aperture of claim 16 wherein the zone comprises four translucent slots.
- 25 18. The masking aperture of claim 16 wherein the intensity in the square ring varies from 0 % to 100 %.
19. The masking aperture of claim 16 wherein the intensity outside the square ring varies from 0% to 99%.
- 30 20. The masking aperture of claim 16 wherein the square ring is combined with one or more zones having a shape selected from the group consisting of square, elliptical, ring, square ring, circular ring, or combinations thereof.
- 35



21. The masking aperture of claim 8 wherein the zones comprise an annular ring and one or more zones with shapes selected from the group of shapes consisting of square, elliptical, ring, square ring, circular ring and combinations thereof.

5 22. A method for controlling on-axis and off-axis illumination of a photomask comprising the steps of:

directing a beam of light of a selected wavelength toward a pupil of an illumination system;

passing the beam of light through a fly's eye lens located near the pupil;

10 diffracting the light through a masking aperture having a half tone diffraction pattern of dithered pixels patterned for distributing the light into two or more zones.

23. The method of claim 22 wherein said half-tone dithered image comprises an array of pixels, each pixel of a clear or opaque type and of the same size, said  
15 clear and opaque pixels for respectively passing and blocking incident light, wherein the number, size, and type of the pixels are chosen in accordance with:

(a) the wavelength of light used to illuminate the photomask, and

(b) the size and shape of the features of the photomask, for generating  
a continuous illumination intensity pattern on the photomask with illumination  
20 intensity at any location controlled by the half-tone dithered image.

24. The masking aperture of claim 23 wherein the half-tone dithered image comprises an array of diffraction elements and each diffraction element is a dithered image of clear or opaque pixels.

25. The method of claim 24 wherein each diffraction element comprise an  $n \times n$  dithered matrix of pixels, the intensity of each element is defined by the number and type of pixels in its dithered matrix and wherein the pixels in each matrix are dithered to avoid artifacts.

26. The method of claim 24 wherein the relative intensity of each subpixel is defined by a recursion relationship where:

$$D^n = \begin{vmatrix} 4D^{n/2} + D_{00}^2 U^{n/2} & 4D^{n/2} + D_{01}^2 U^{n/2} \\ 4D^{n/2} + D_{10}^2 U^{n/2} & 4D^{n/2} + D_{11}^2 U^{n/2} \end{vmatrix}$$

5

where:

$$U^n = \begin{vmatrix} 1 & 1 & \dots & 1 \\ 1 & & & \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ 1 & & & \end{vmatrix}$$

- 10 27. The method of claim 26 wherein the matrix of pixels comprises an 8 x 8 matrix and the relative intensity, D8, comprises:

$$D^8 = \begin{vmatrix} 0 & 32 & 8 & 40 & 2 & 34 & 10 & 42 \\ 48 & 16 & 56 & 24 & 50 & 18 & 58 & 26 \\ 12 & 44 & 4 & 36 & 14 & 46 & 6 & 38 \\ 60 & 28 & 52 & 20 & 62 & 30 & 54 & 22 \\ 3 & 35 & 11 & 43 & 1 & 33 & 9 & 41 \\ 51 & 19 & 59 & 27 & 49 & 17 & 57 & 25 \\ 15 & 47 & 7 & 39 & 13 & 45 & 5 & 37 \\ 63 & 31 & 55 & 23 & 61 & 29 & 53 & 21 \end{vmatrix}$$

15

28. The method of claim 25 wherein the matrix of diffracting elements is selected from the group consisting of 2 x 2, 4 x 4, 8 x 8, 16 x 16, 32 x 32 and 64 x 64.

20

29. The method of claim 22 further comprising the step of forming two or more zones.

30. The method of claim 29 wherein the zones are arranged symmetrically about the center of the masking aperture.

25

31. The method of claim 29 wherein the zones are arranged asymmetrically about the center of the masking aperture.

32. The method of claim 29 the zones have one shape selected from the group consisting of circles, squares, rectangles, ellipses, rings, circular rings, square rings and combinations thereof.

33. The method of claim 29 wherein the selected shape is a stepped square.

34. The method of claim 29 wherein the zone(s) is shaped in an ellipse and the major axis of each ellipse is aligned at a 45 degree angle with respect to the center of the masking aperture.

35. An illumination system comprising:

a light source for emitting light of selected wavelength(s) in an optical path toward a pupil,

means for shaping the light from the source into a shaped illumination pattern having one or more zones where the intensity of the light in the zones varies to produce a shaped illumination pattern for each zones;

means for optically integrating light incident on the pupil;

a square shaped aperture disposed proximate the pupil for squaring the edges of the shaped illumination distribution pattern; and

optical means for combining the shaped illumination to illuminate a photomask.

36. The illumination system of claim 35 wherein the means for shaping the light comprises a plurality of masking apertures.

37. The illumination system of claim 36 wherein one of the masking apertures comprises an opaque plate with one or more apertures.

38. The illumination system of claim 37 wherein one of the masking apertures comprises a translucent plate with a central obscuration.

39. The illumination system of claim 38 wherein the obscuration is circular or square.
- 5 40. The illumination system of claim 35 wherein the means for optically integrating light is a fly's eye lens.
41. The illumination system of claim 35 wherein the square shaped aperture comprises a translucent substrate and a square pattern or a metal plate with a square  
10 aperture.
42. The illumination system of claim 35 wherein the shaped illumination pattern has a shape selected from the group consisting of round, square, and elliptical shapes.
- 15 43. The illumination system of claim 42 wherein the means for shaping the light comprises one or more diffractive optical elements.
44. The illumination system of claim 42 wherein the means for shaping the light from the source comprises one or more beam splitters located between the source of  
20 light and the pupil.
45. The illumination system of claim 44 wherein the optical means for combining the shaped illumination pattern comprises a refractive element for each beam.
- 25 46. The illumination system of claim 35 wherein the means for shaping an illumination pattern comprises a masking aperture comprising:  
a translucent substrate;  
a half-tone dithered image on the substrate, said half-tone dithered image comprising an array of pixels, each pixel of a clear or opaque type and of the same  
30 size, said clear and opaque pixels for respectively passing and blocking incident light, wherein the number, size, and type of the pixels are chosen in accordance with:  
(a) the wavelength of light used to illuminate the photomask, and  
(b) the size and shape of the features of the photomask, for generating a continuous illumination intensity pattern on the photomask with illumination

intensity at any location controlled by the half-tone dithered image.

47. The illumination system of claim 46 wherein the half-tone dithered image comprises an array of diffraction elements and each diffraction element is a dither image of clear or opaque pixels.

48. The illumination system of claim 46 wherein the square aperture is formed the same as the dithered image.

49. The illumination system of claim 47 wherein each diffraction element pixel comprises an  $n \times n$  dithered matrix of pixels, the intensity of each element is defined by the number and type of pixels in its dithered matrix and wherein the pixels in each matrix are dithered to avoid artifacts.

50. The illumination system of claim 47 wherein the relative intensity of each subpixel is defined by a recursion relationship where:

$$D^n = \begin{vmatrix} 4D^{n/2} + D_{00}^2 U^{n/2} & 4D^{n/2} + D_{01}^2 U^{n/2} \\ 4D^{n/2} + D_{10}^2 U^{n/2} & 4D^{n/2} + D_{11}^2 U^{n/2} \end{vmatrix}$$

where:

$$U^n = \begin{vmatrix} 1 & 1 & \dots & 1 \\ 1 & & & \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ 1 & & & \end{vmatrix}$$

57. The illumination system of claim 50 wherein the matrix of pixels comprises an  $8 \times 8$  matrix and the relative intensity,  $D_8$ , comprises :

$$D^8 = \begin{vmatrix} 0 & 32 & 8 & 40 & 2 & 34 & 10 & 42 \\ 48 & 16 & 56 & 24 & 50 & 18 & 58 & 26 \\ 12 & 44 & 4 & 36 & 14 & 46 & 6 & 38 \\ 60 & 28 & 52 & 20 & 62 & 30 & 54 & 22 \\ 3 & 35 & 11 & 43 & 1 & 33 & 9 & 41 \\ 51 & 19 & 59 & 27 & 49 & 17 & 57 & 25 \\ 15 & 47 & 7 & 39 & 13 & 45 & 5 & 37 \\ 63 & 31 & 55 & 23 & 61 & 29 & 53 & 21 \end{vmatrix}$$

52. The system of claim 35 wherein the means for optically integrating light on  
5 the pupil is a plurality of fly's eye lenses.

53. An illumination system comprising:

a light source for emitting light of selected wavelength(s) in an optical path  
toward a pupil,

10 means for shaping the light from the source into a shaped illumination pattern  
having one or more zones where the intensity of the light in the zones varies to  
produce a shaped illumination pattern for each zones and wherein the zone is shaped  
from the group consisting of ellipses, square rings, stepped square rings and  
combinations thereof;

15 means for optically integrating light incident on the pupil; and  
optical means for combining the shaped illumination to illuminate a  
photomask.

54. The illumination system of claim 53 further comprising means for shaping the  
20 light into additional patterns selected from the group consisting of circles, squares,  
rectangles and circular rings.

55. A method for controlling on-axis and off-axis illumination of a photomask  
comprising the steps of:

25 directing a beam of light of a selected wavelength toward a pupil of an  
illumination system;

passing the beam of light through a fly's eye lens located near the pupil;

diffracting the light to form a pattern of illumination intensity in one or more

zones wherein each zone has a shape corresponding to shapes selected from the group consisting of ellipses, square rings, stepped squares and combinations thereof.

56. The method of claim 55 further diffracting the light beam to form one or more  
5 additional patterns of light intensity selected from the group consisting of circles, squares, rectangles and circular rings.

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## ABSTRACT

A masking aperture for a photomask illumination system provides controlled on-axis and off-axis illumination. The masking aperture has a dithered pattern of  
5 pixels. The intensity of the pattern controls the illumination of the photomask. The masking aperture pattern defines one or more zones of illumination. Zones comprise elements that are patterned in accordance with a selected wavelength of incident light to diffract the incident light into an illumination pattern for illuminating a photomask. Each of the elements is constructed with a matrix of pixels. In the preferred  
10 embodiment the array of pixels is 8 x 8. The number of elements is generally greater than 3 x 3.

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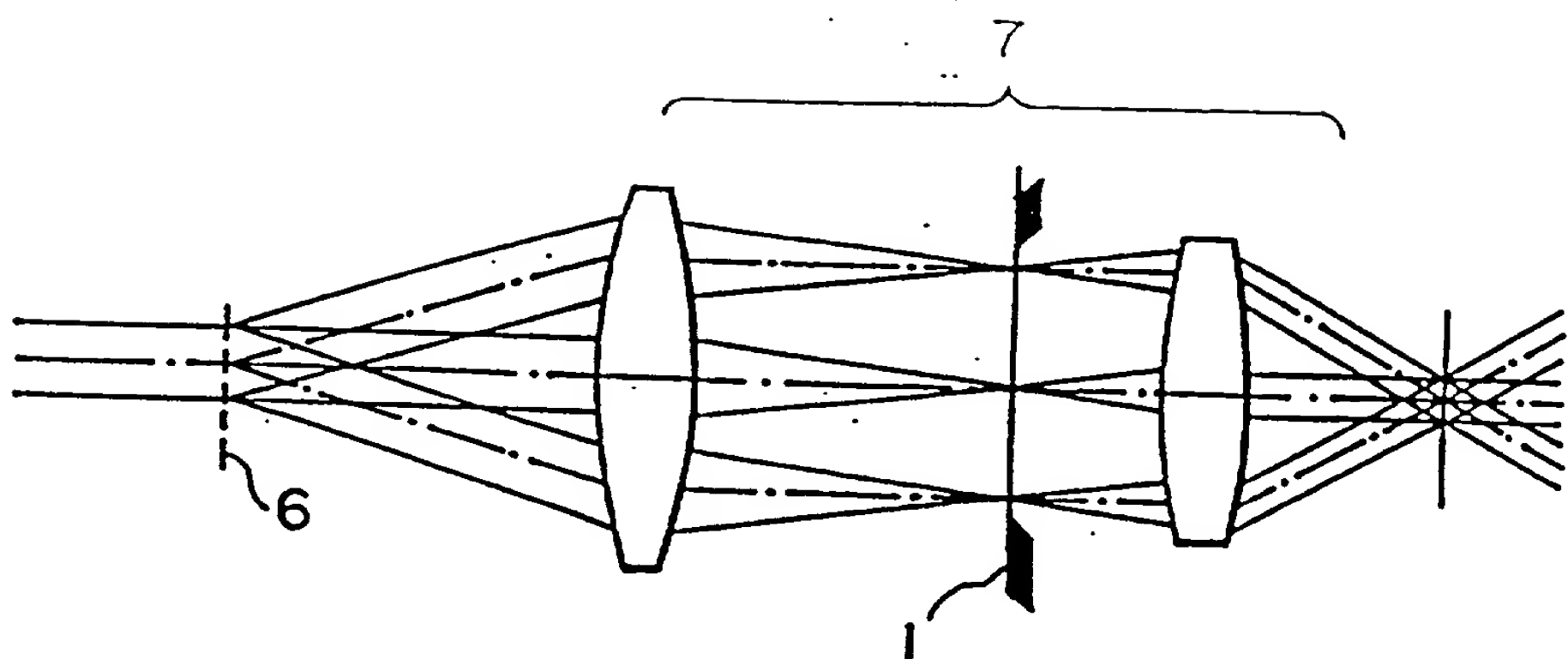


FIG. 1a

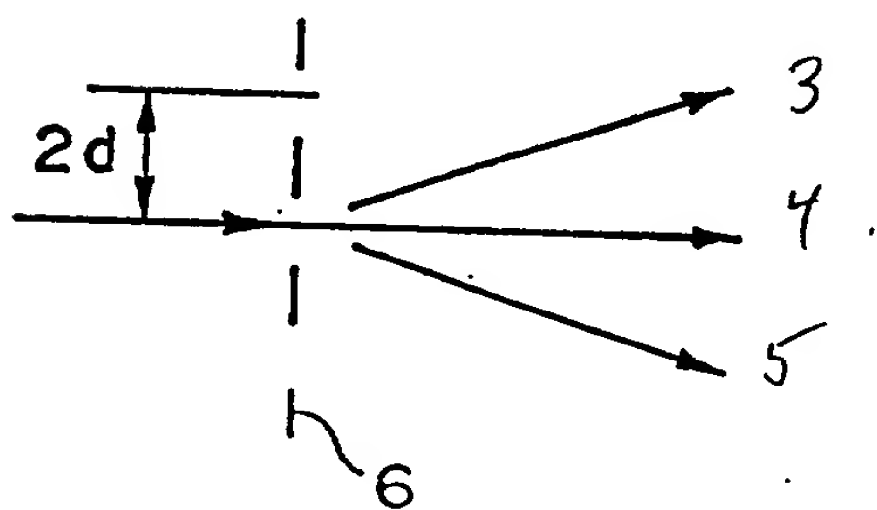


FIG. 1b

00423300 102199

Figure 1

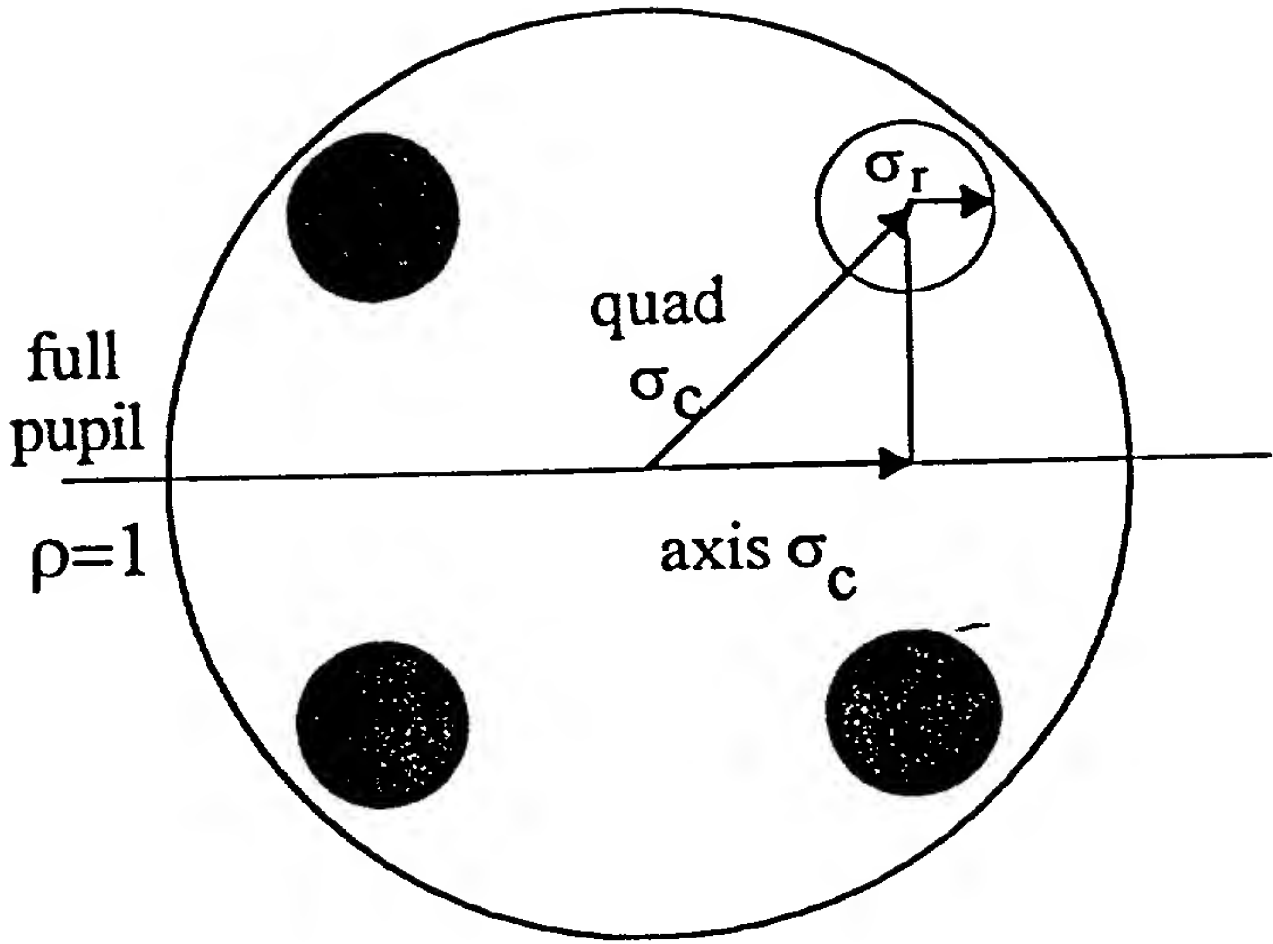


Figure 2

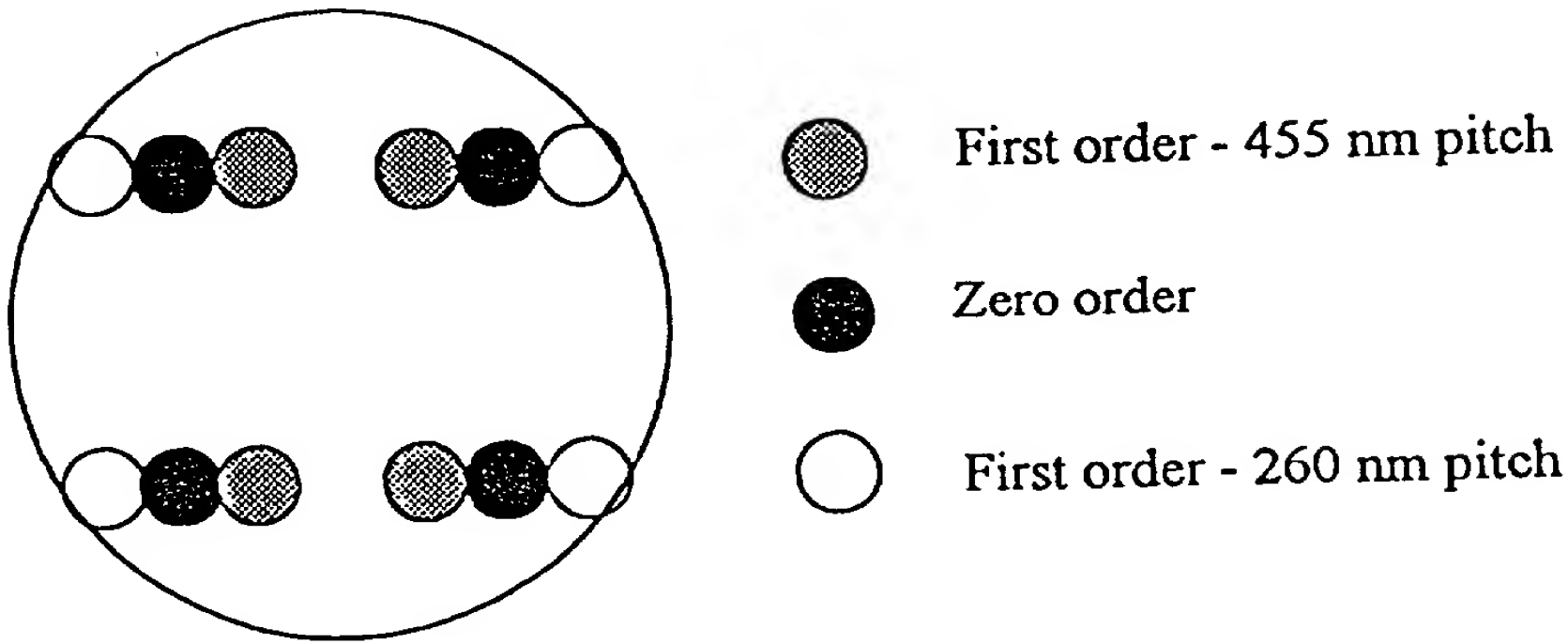
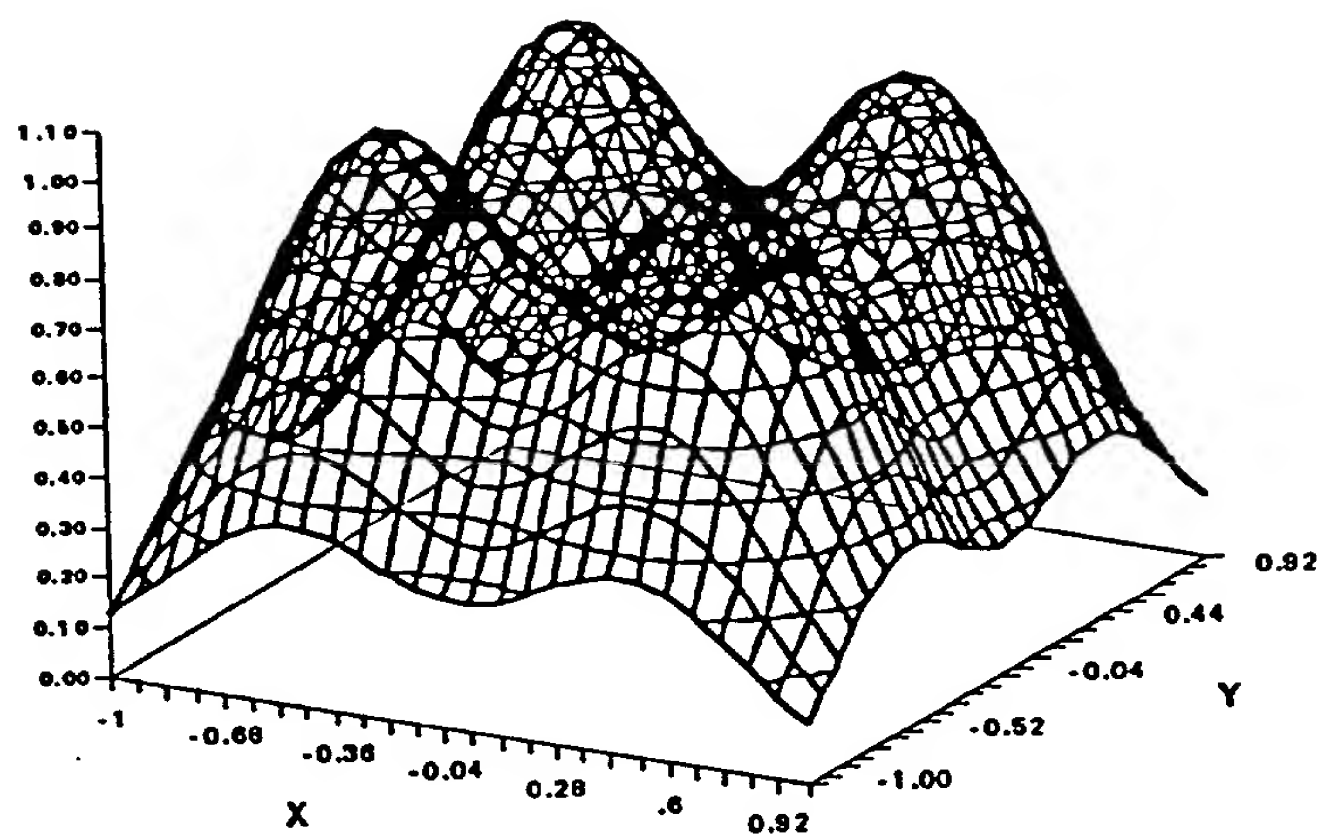


Figure 3



09422390-102199  
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Figure 4

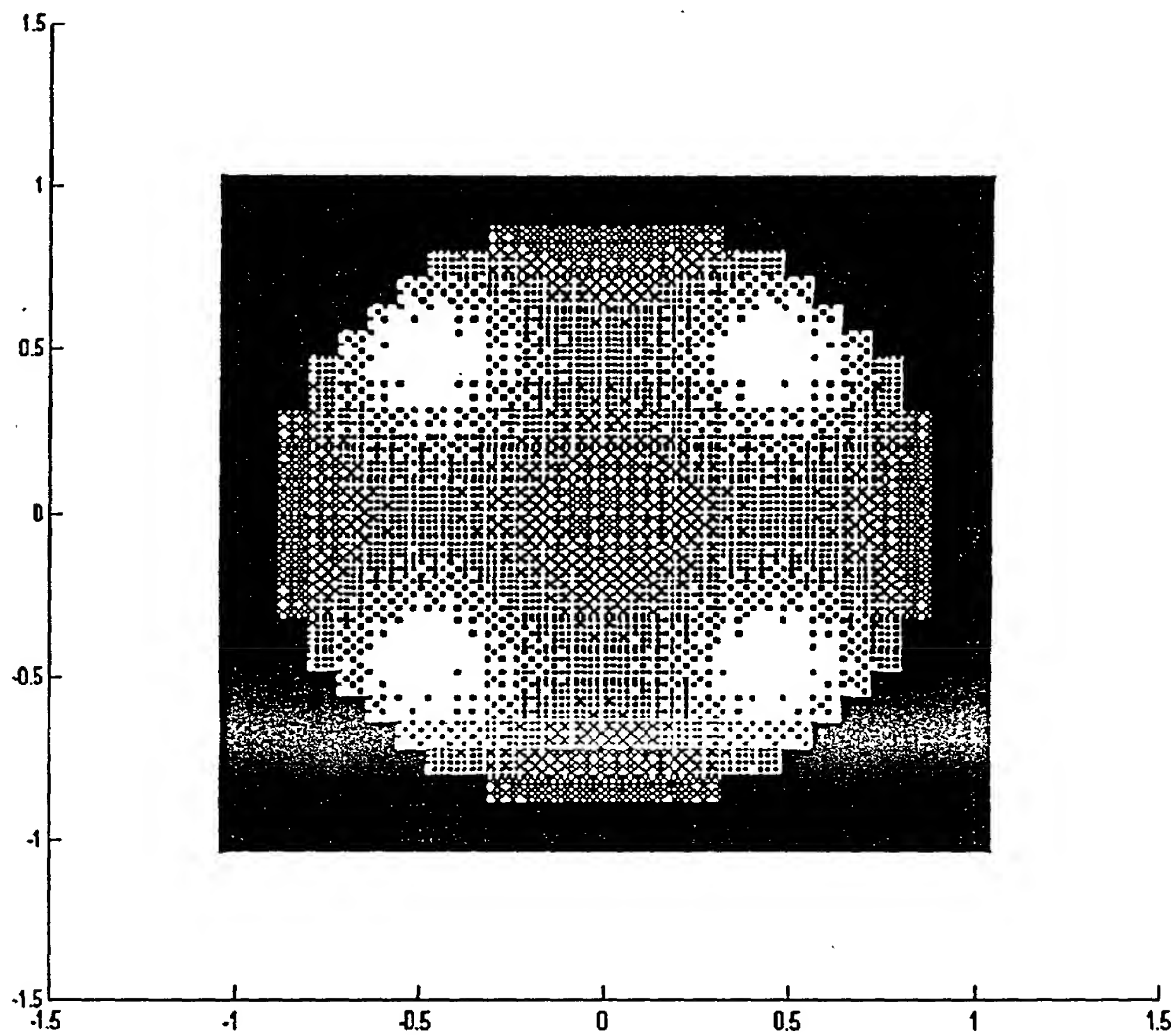
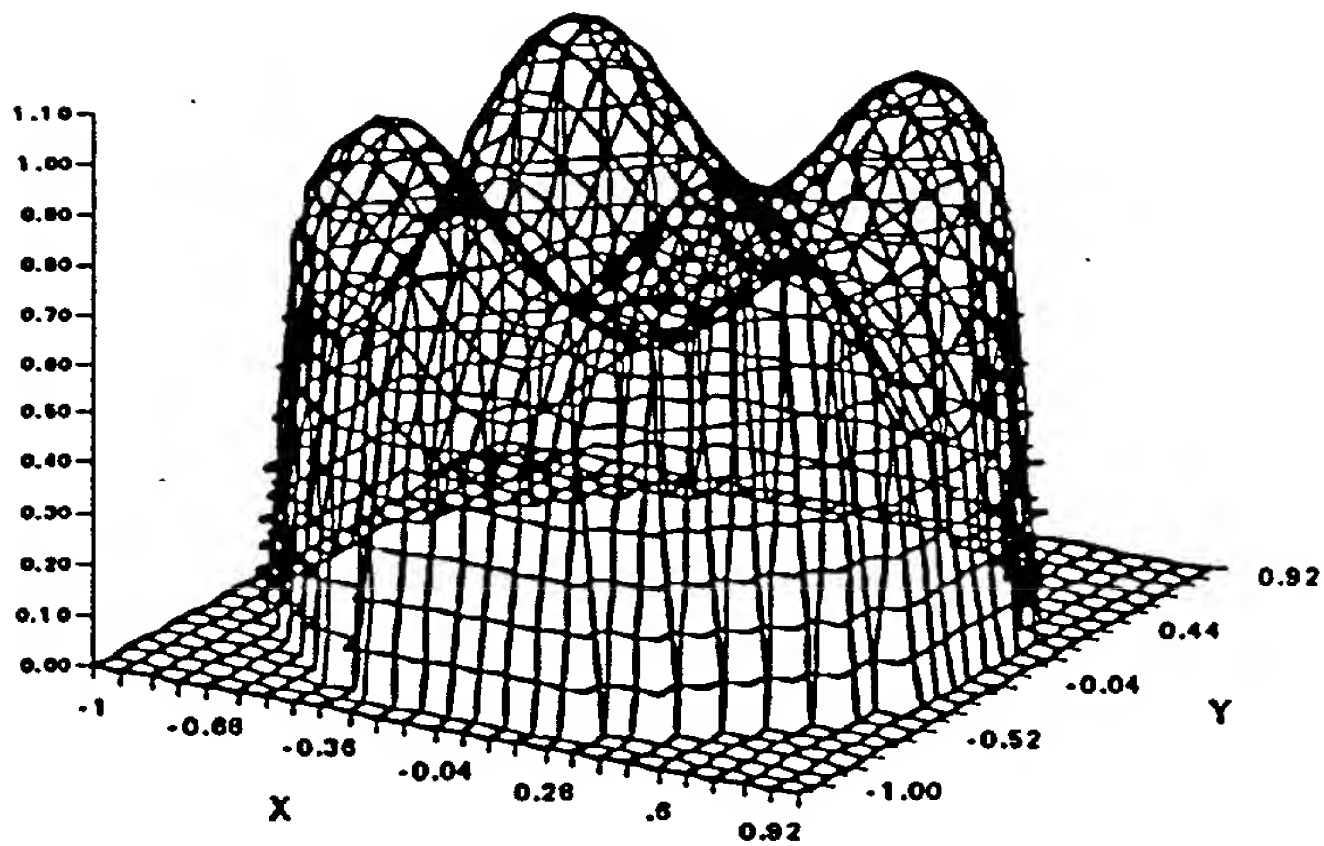
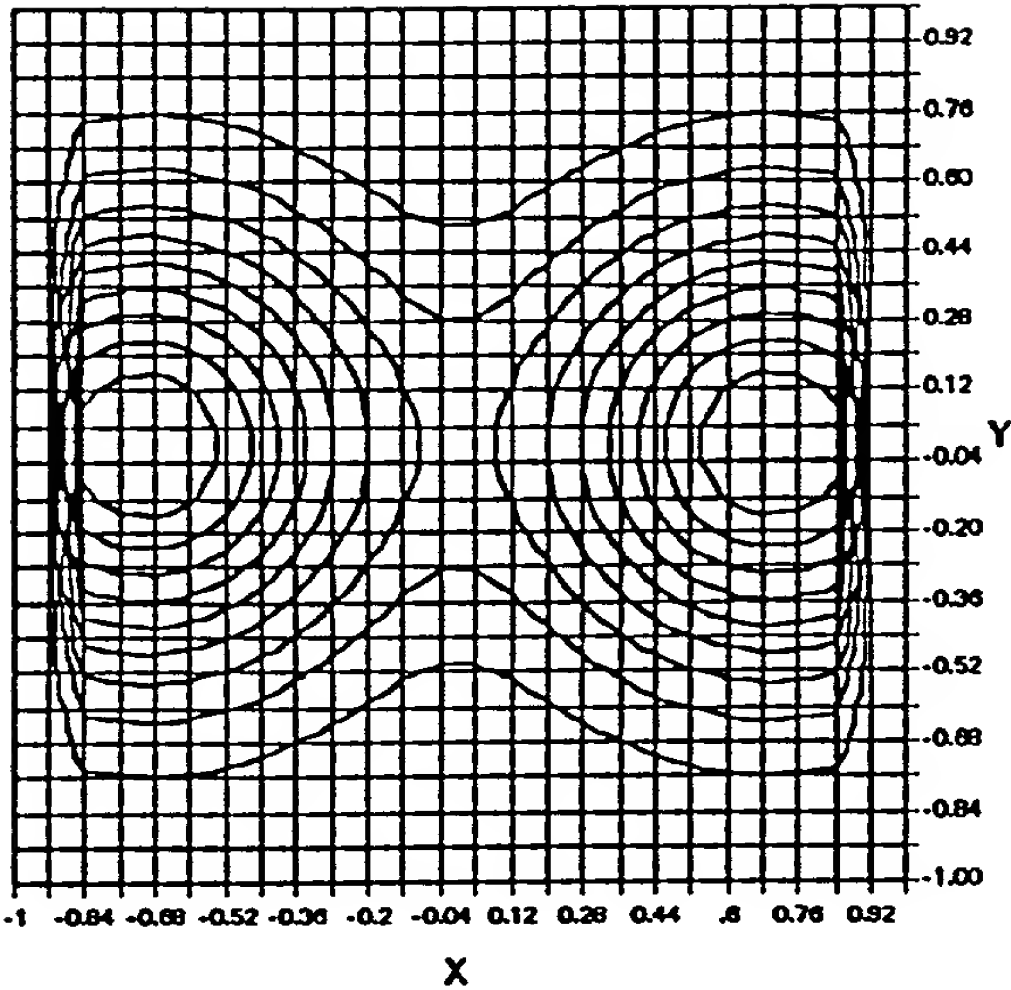


Figure 5



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Figure 6



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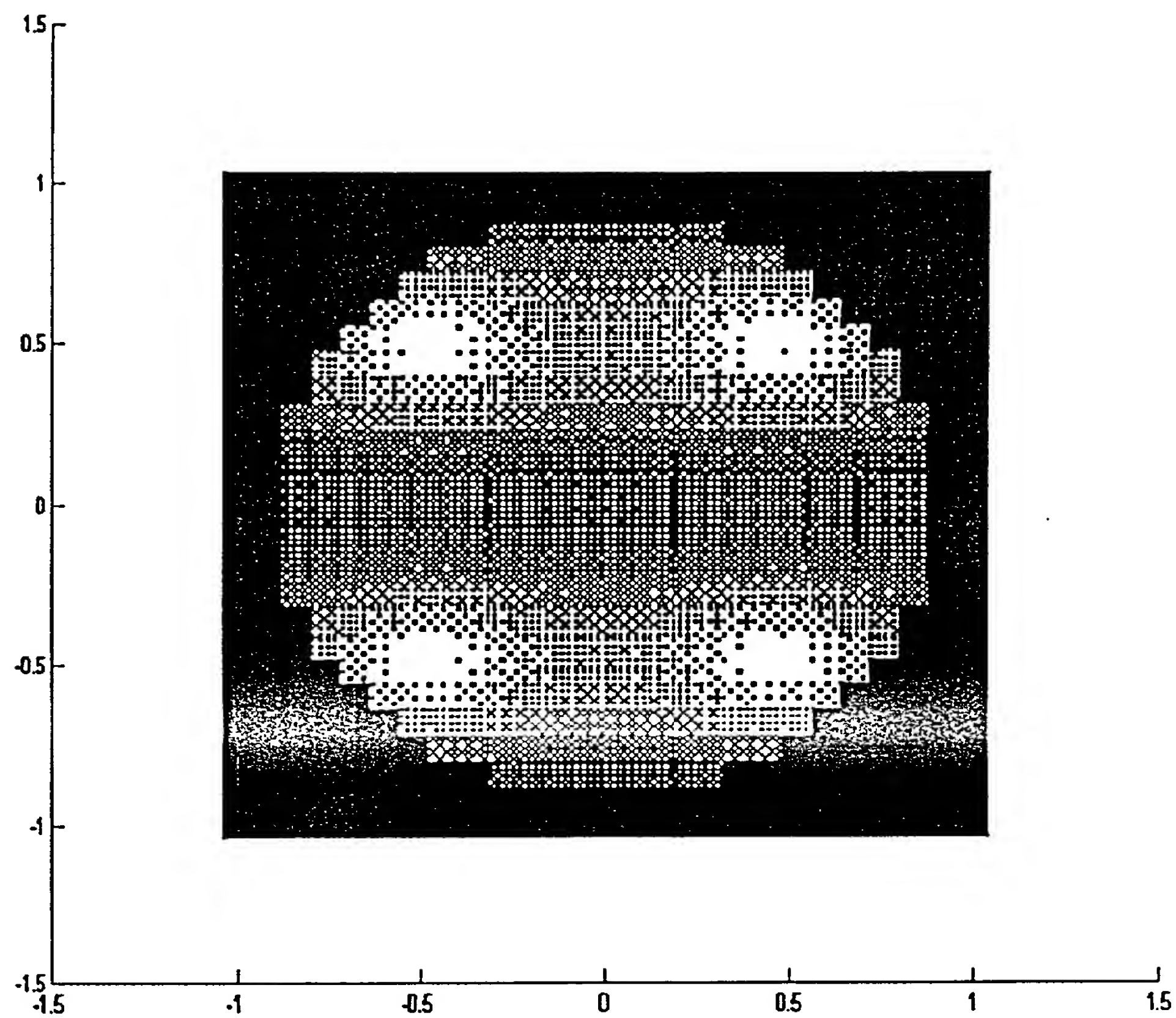
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Figure 8

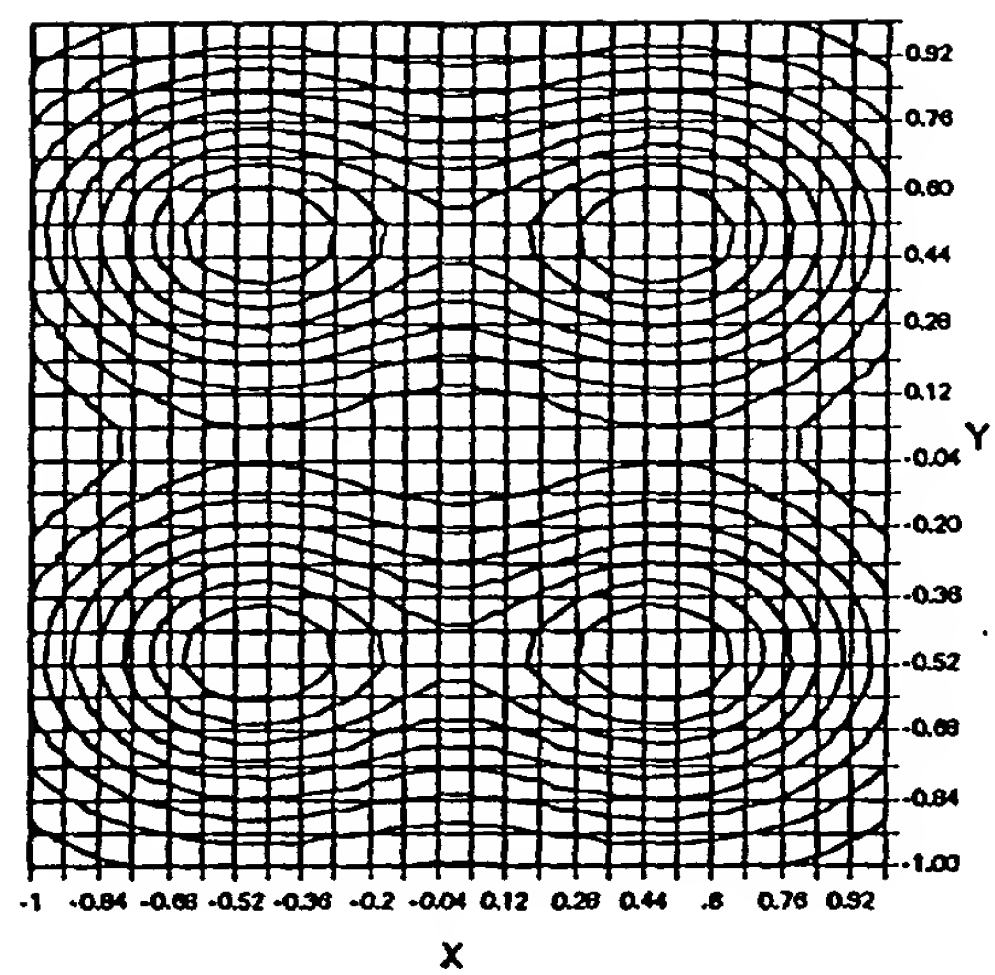


Figure 9

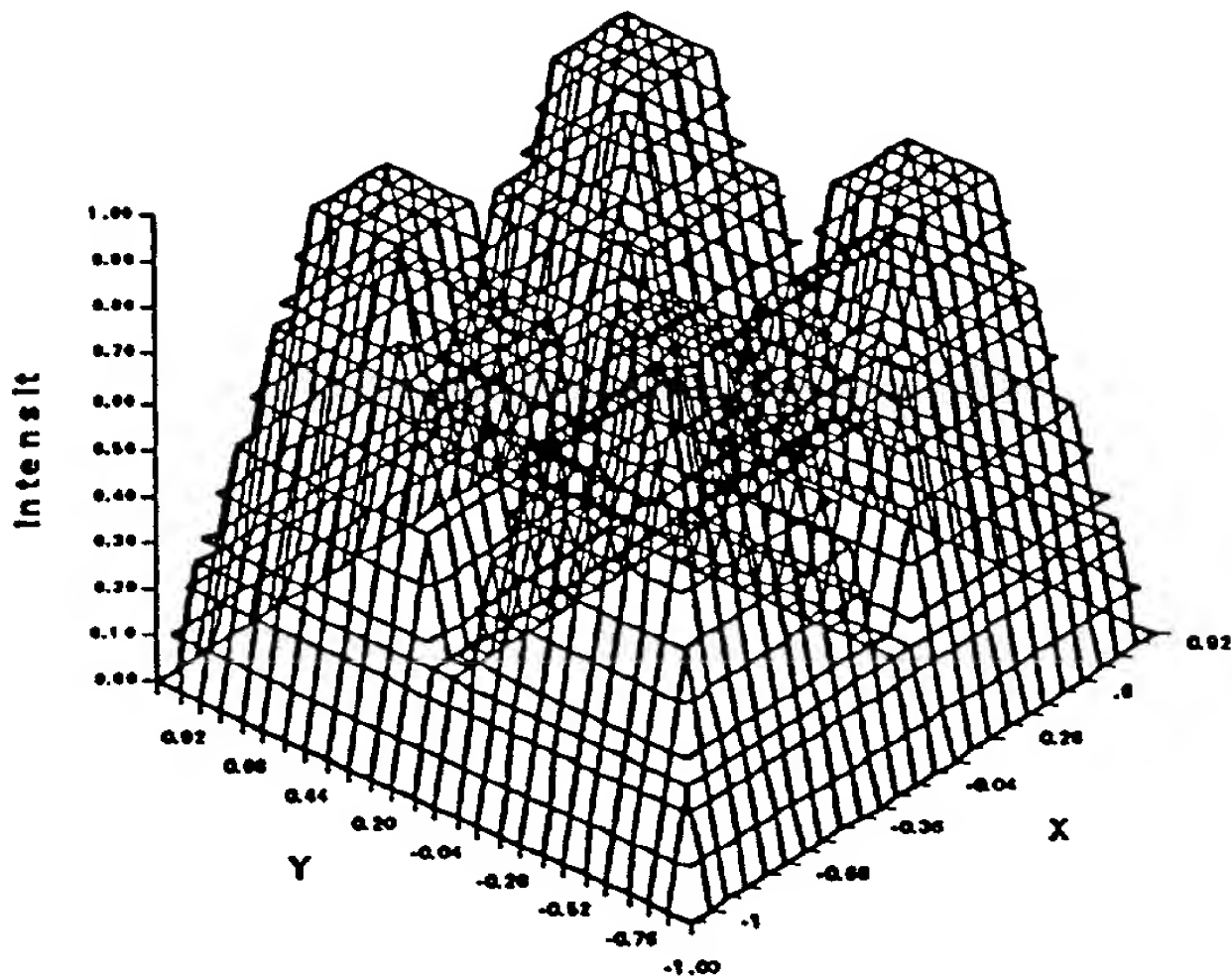


Figure 10

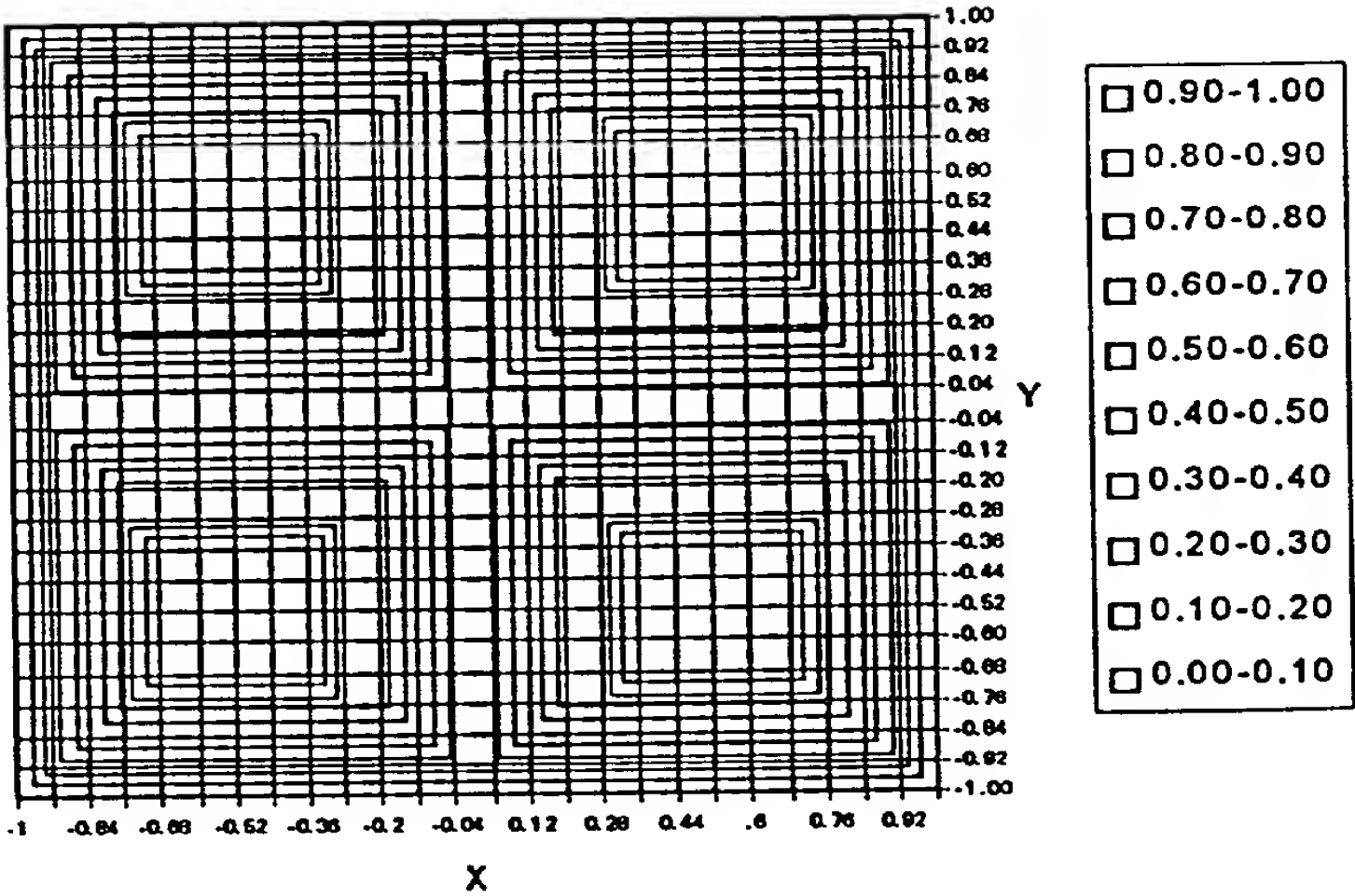
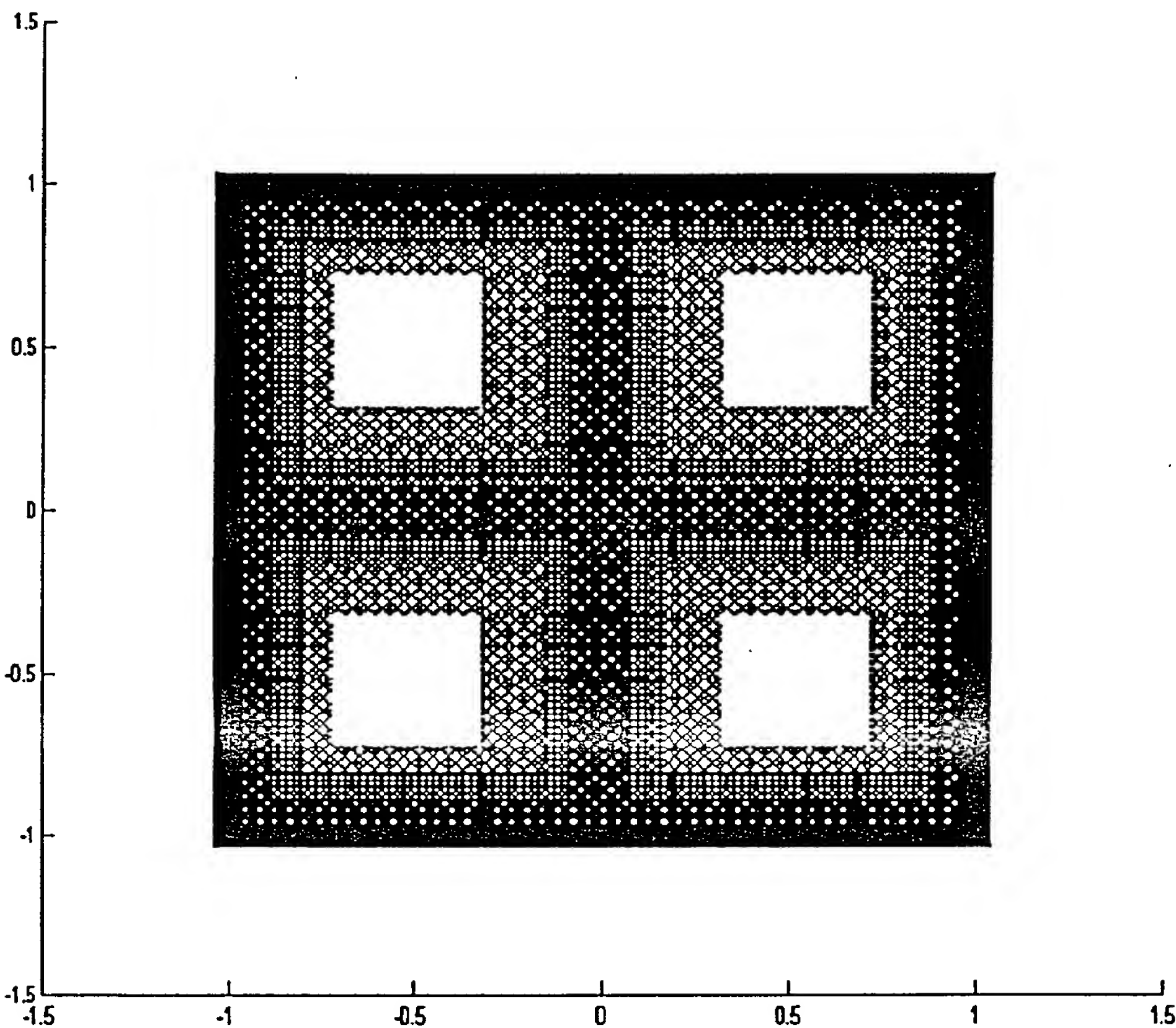
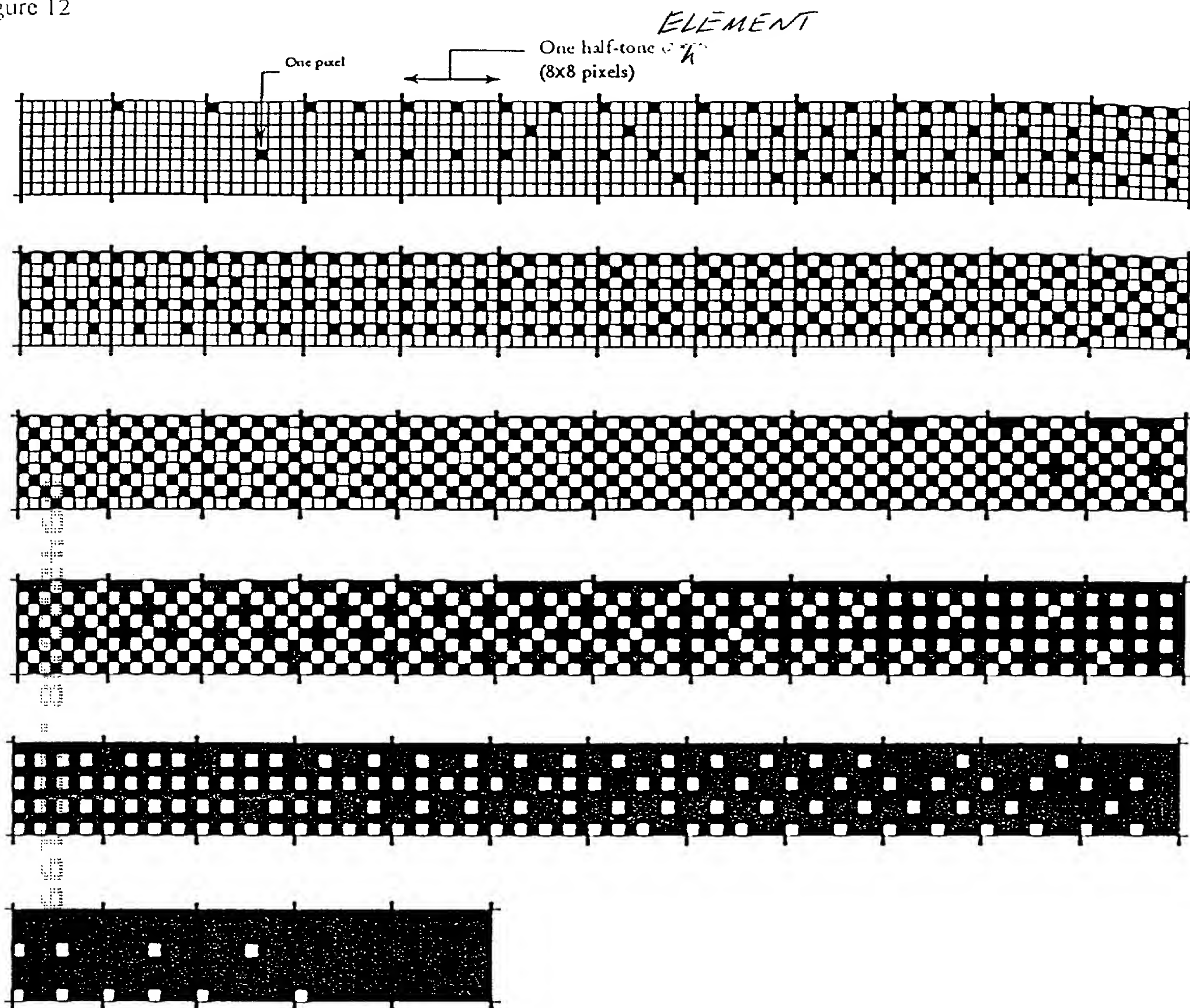


Figure 11

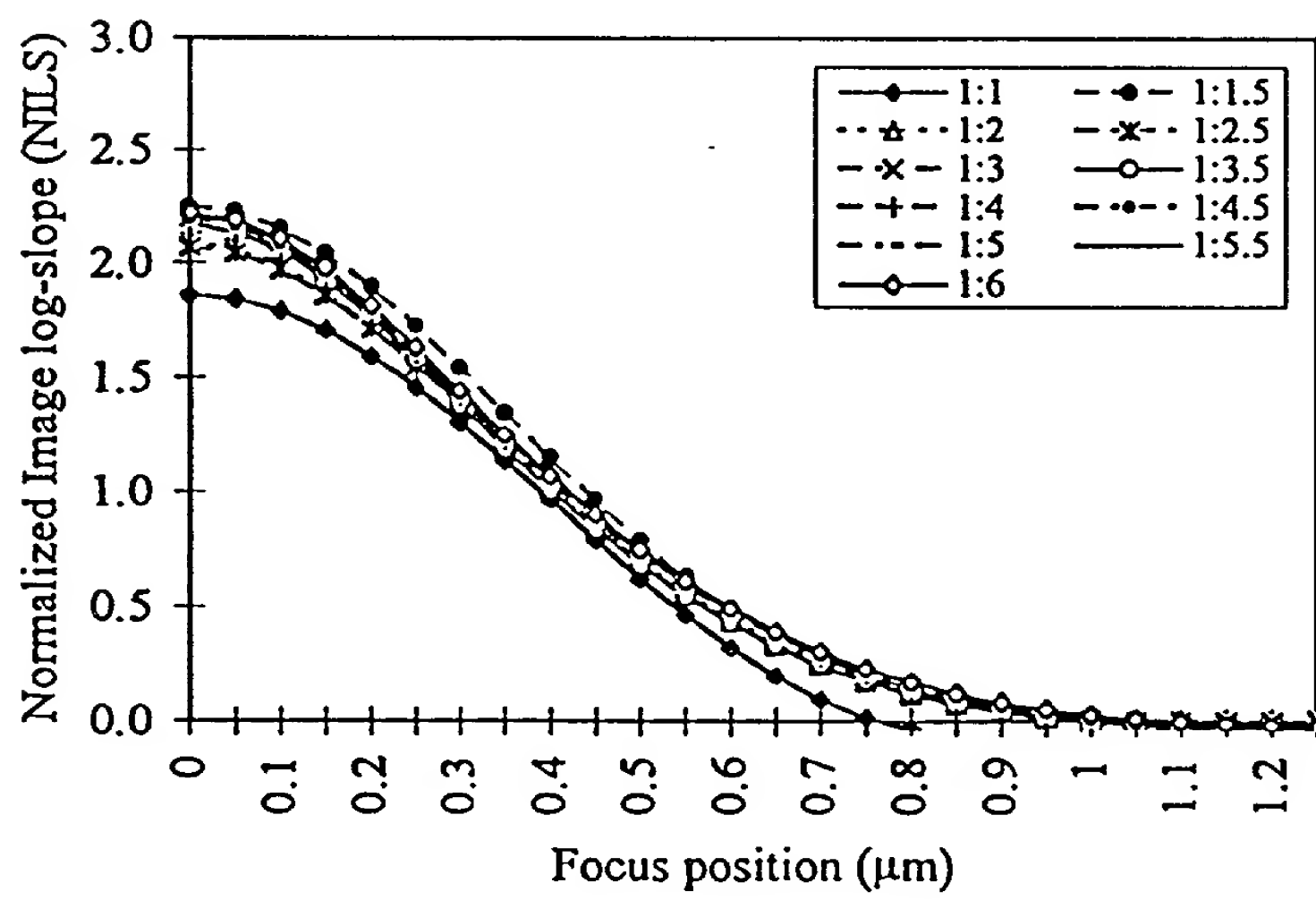


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Figure 12



**Figure 1**



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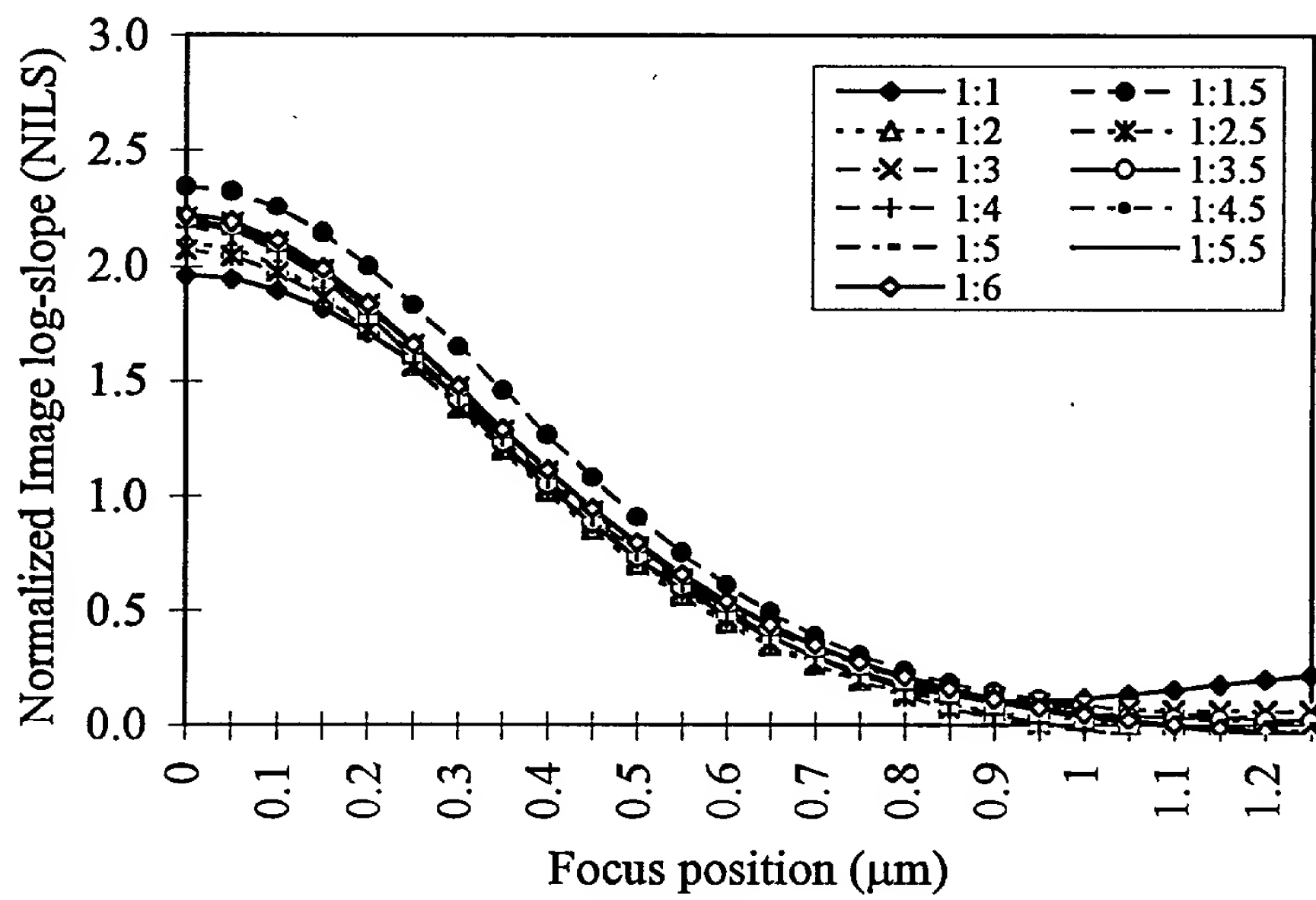
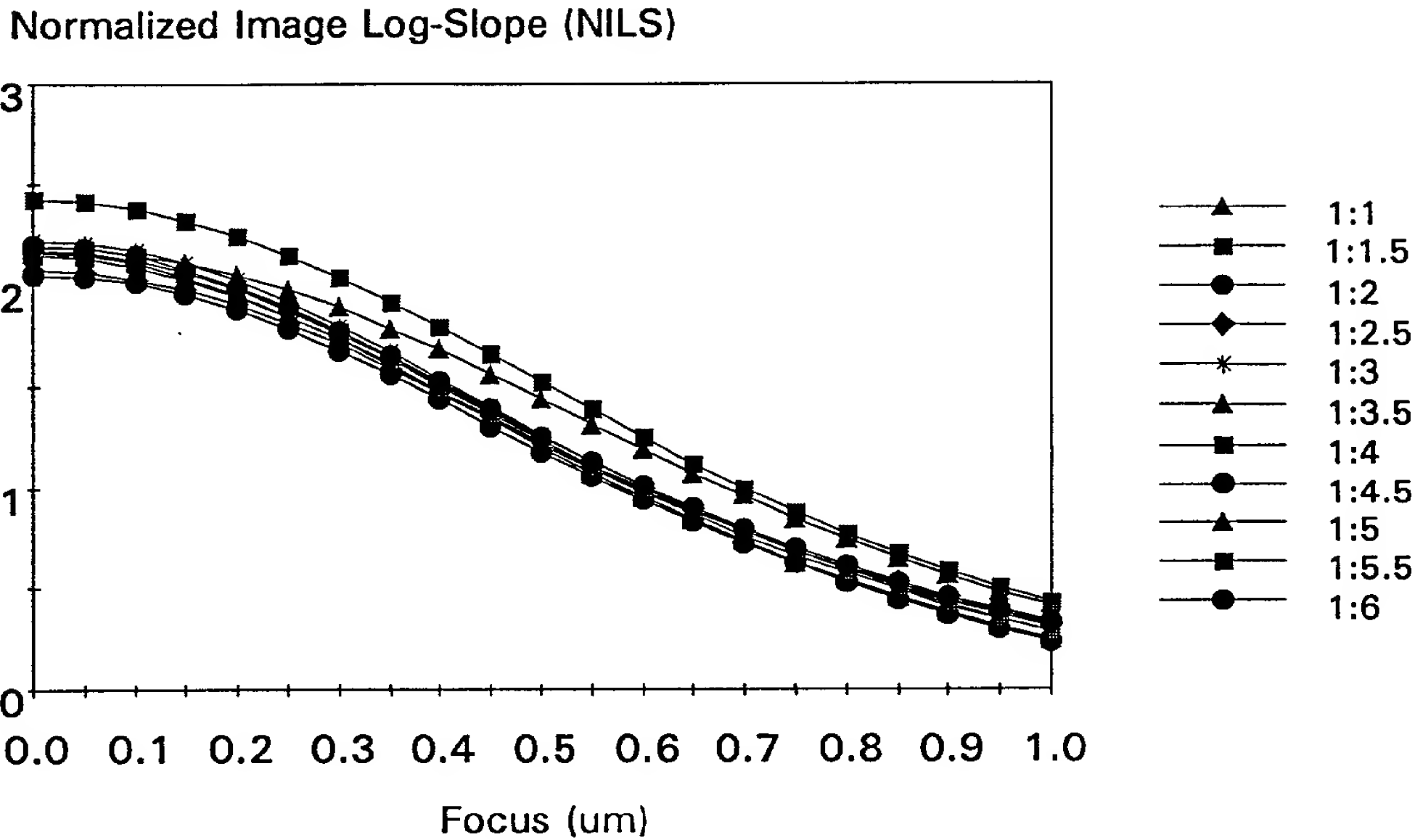




Figure 15b



004233-1049  
667207-262460

Figure 15c

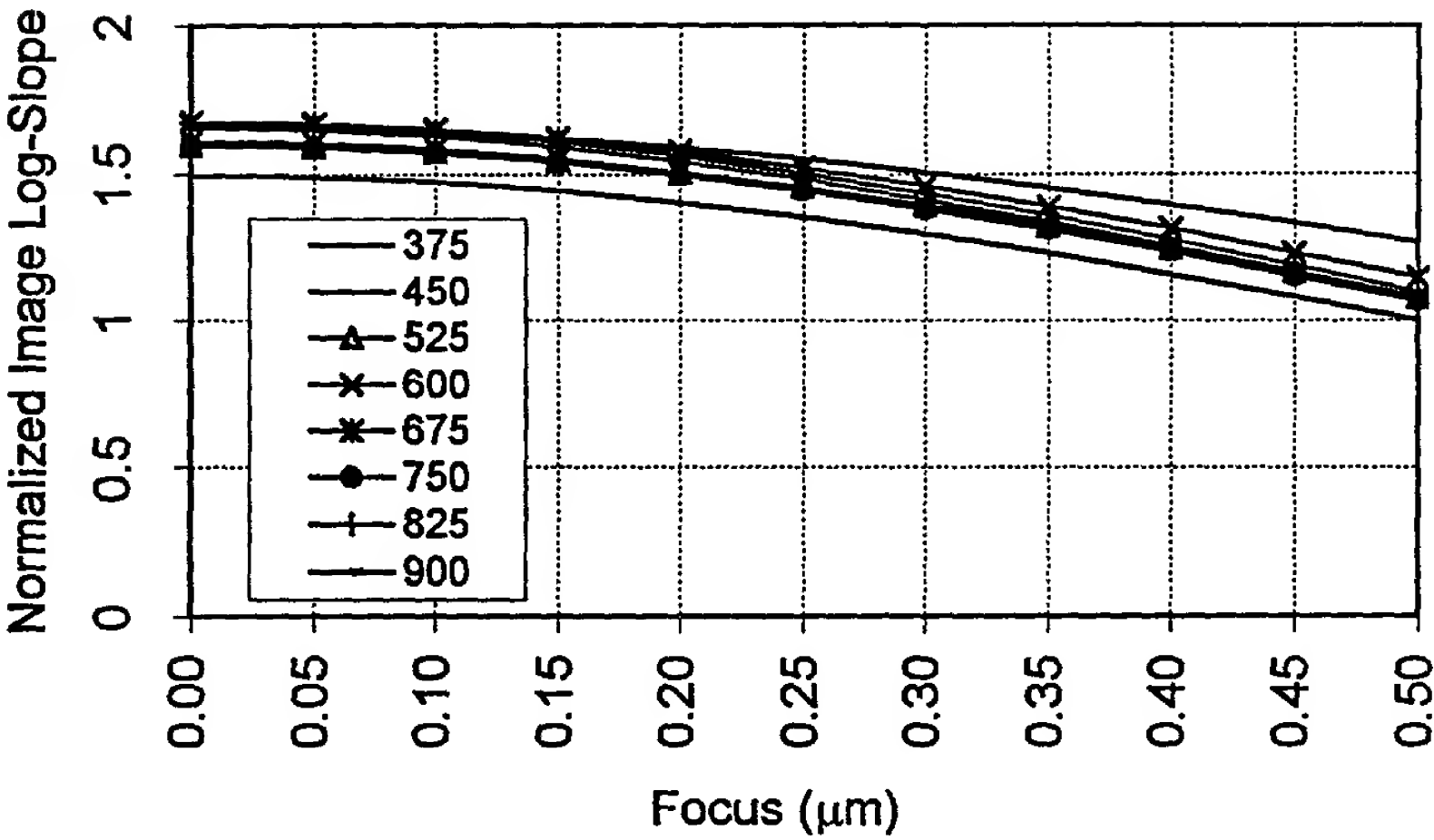


Figure 15d

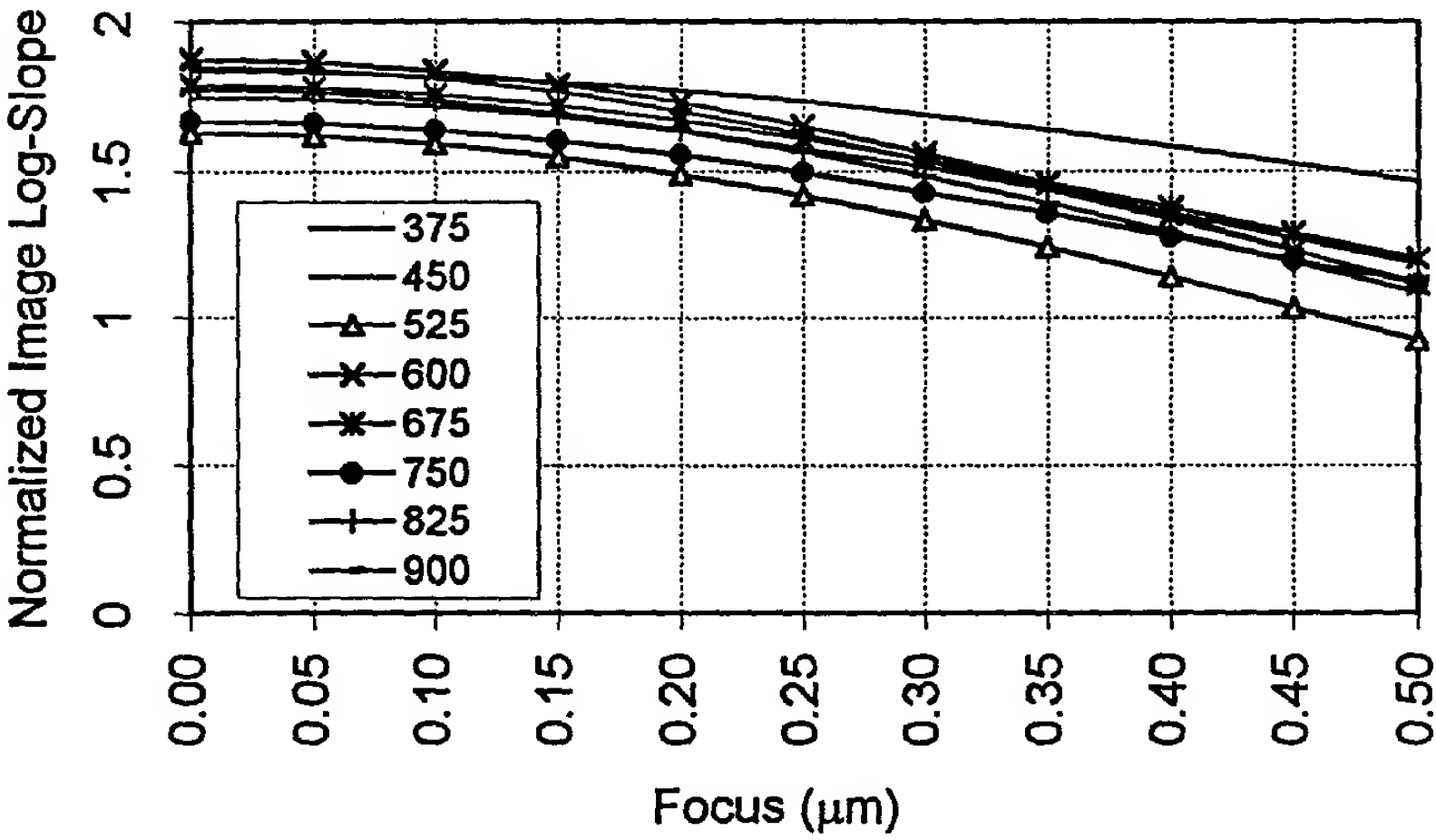


Figure 16

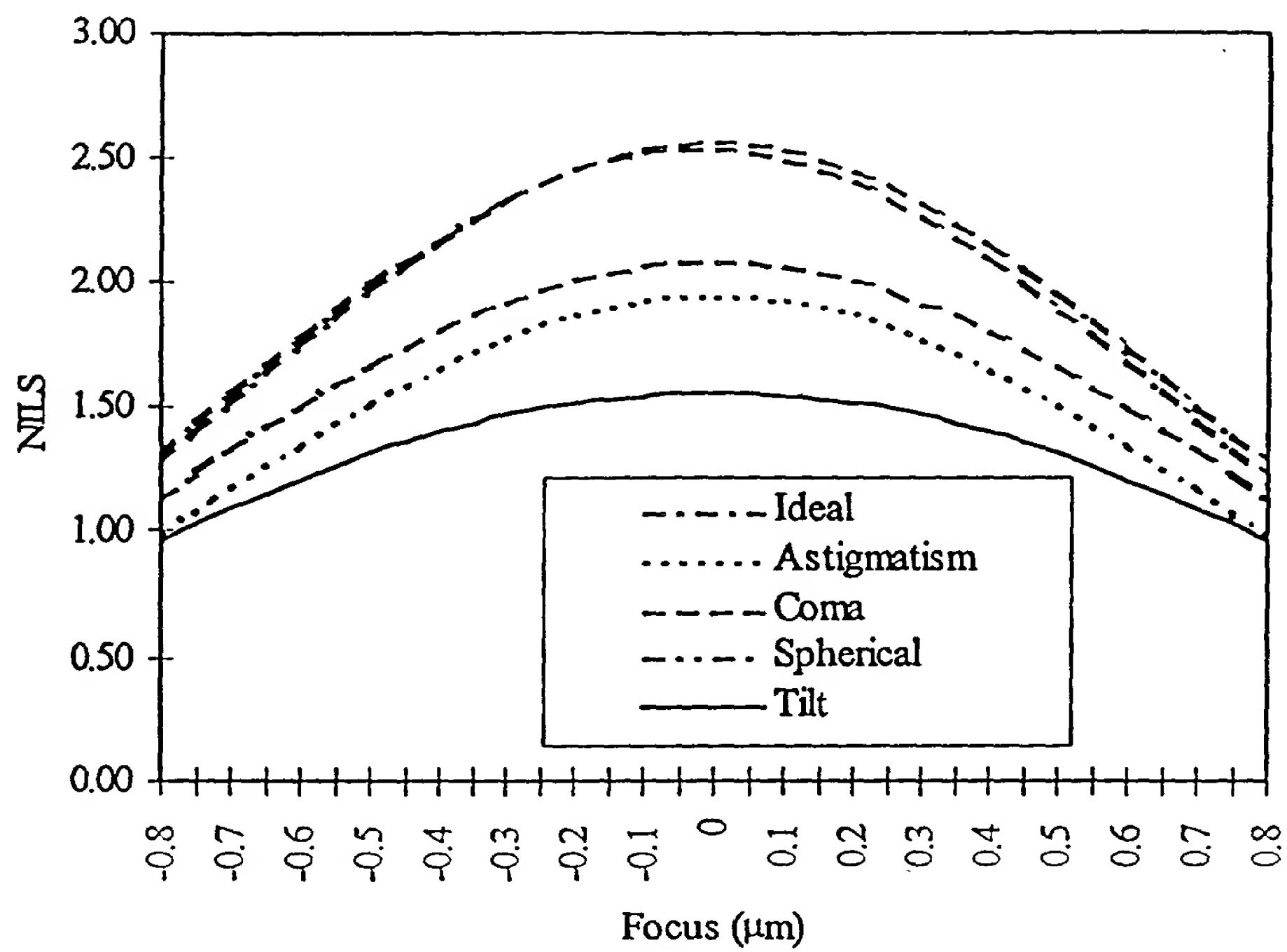
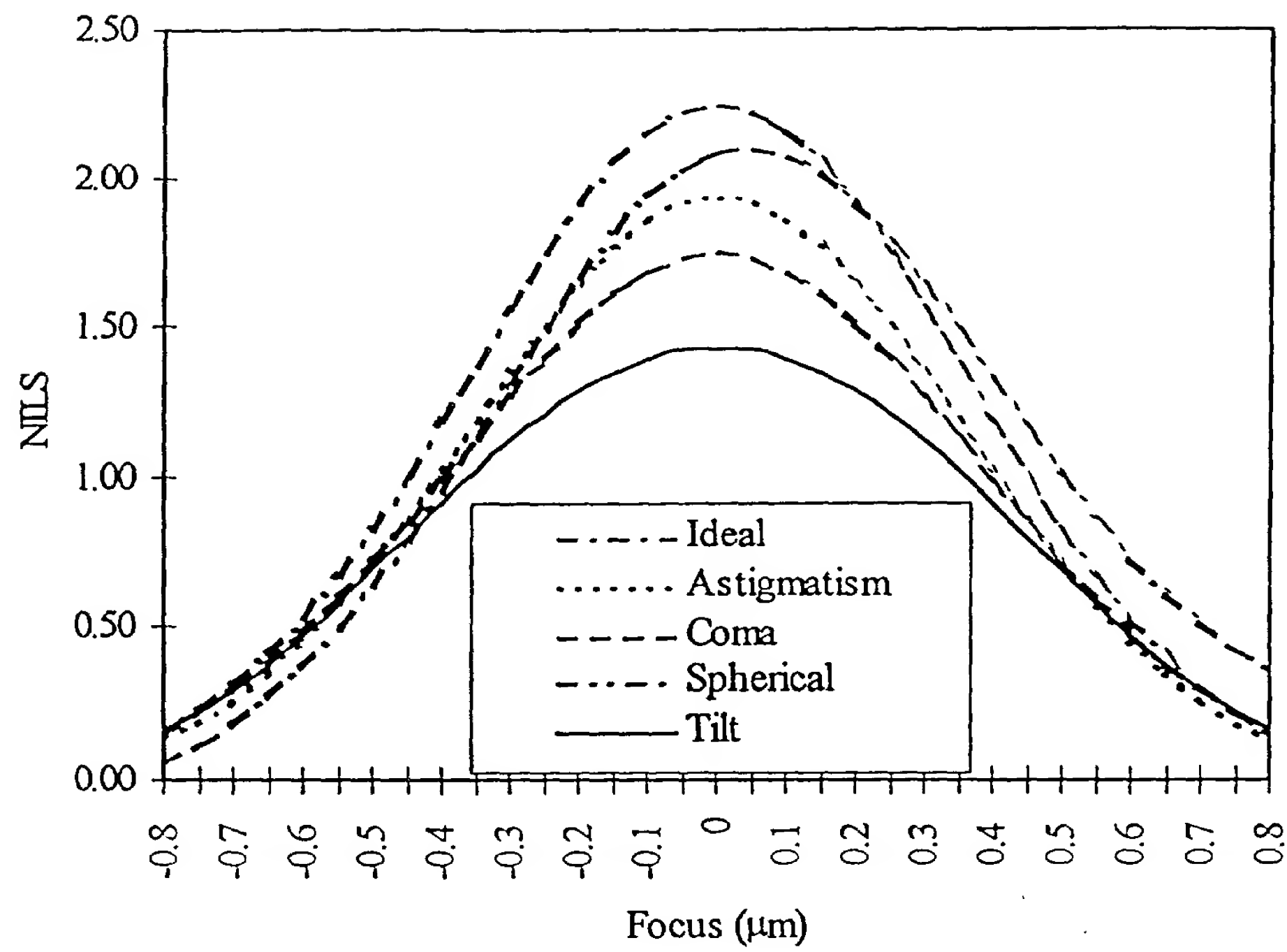
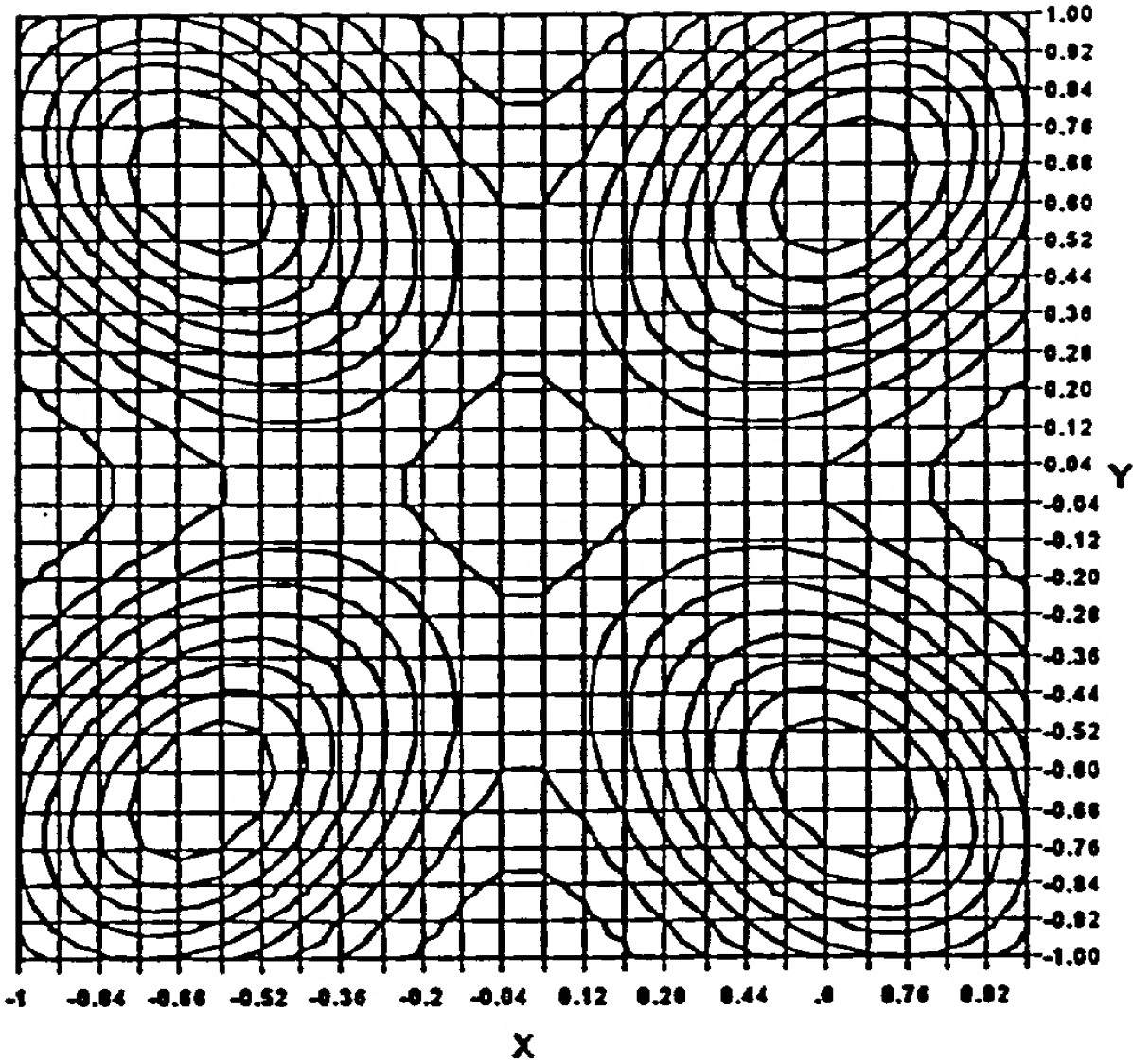


Figure 17



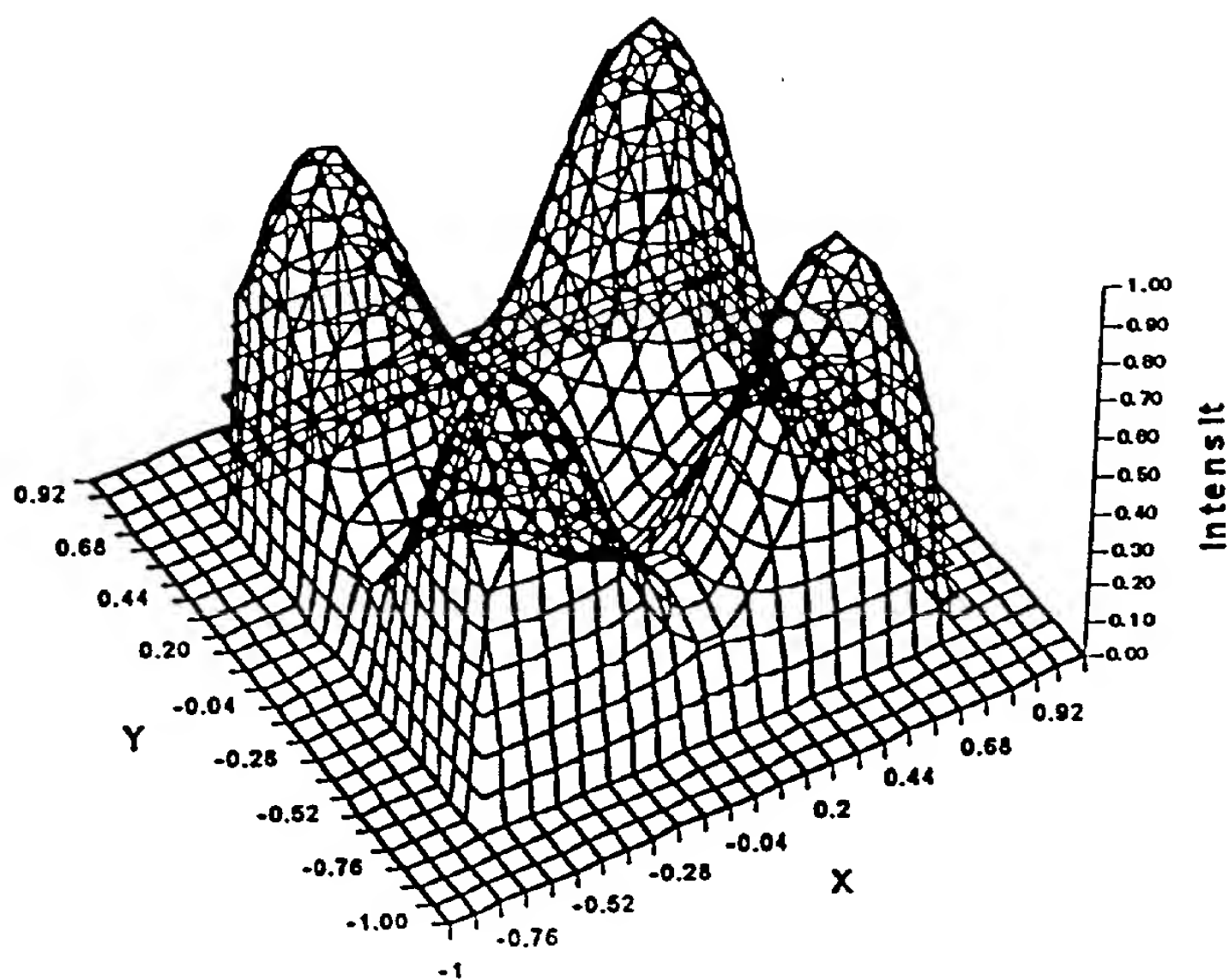
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Figure 18.



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Figure 19



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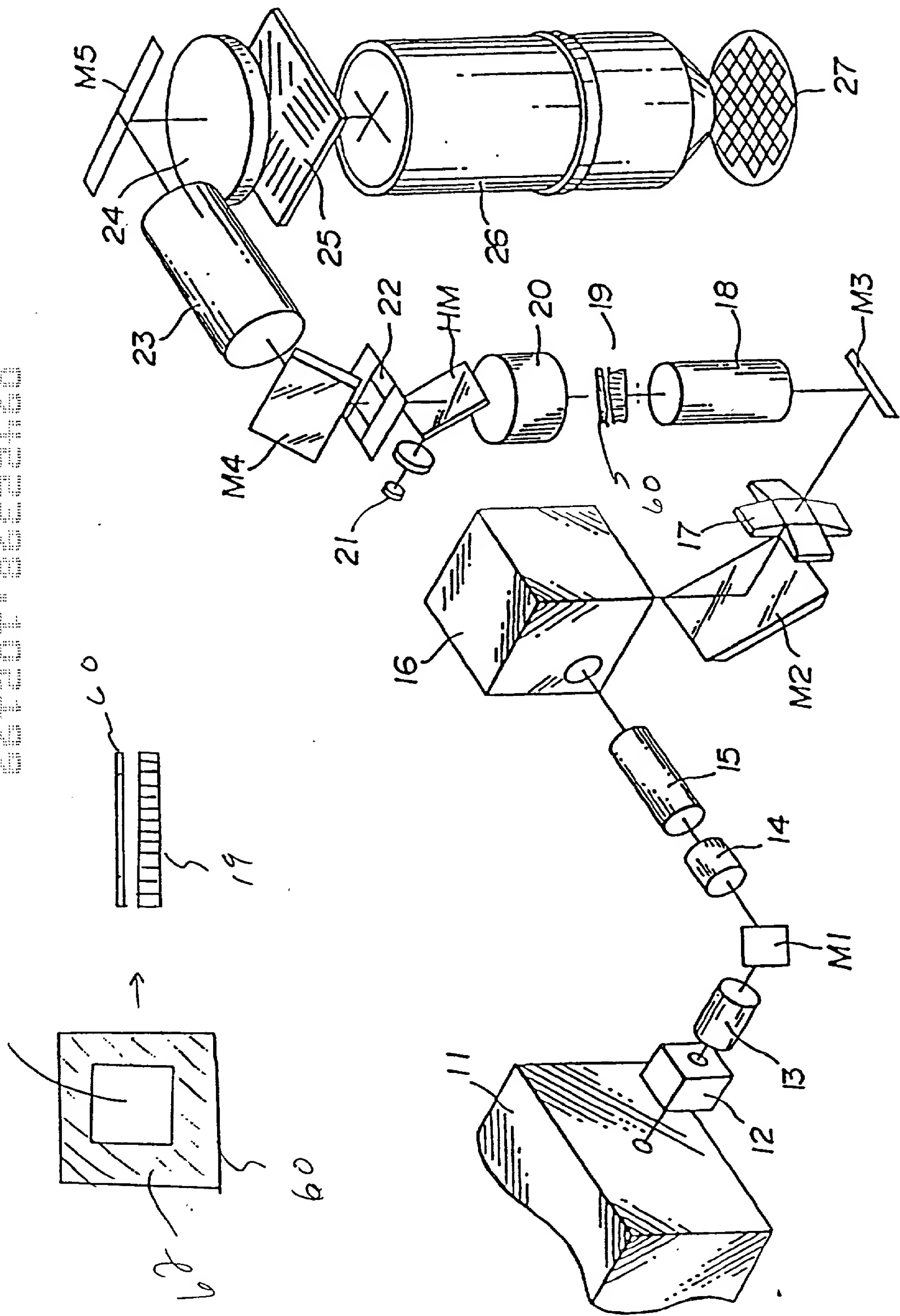
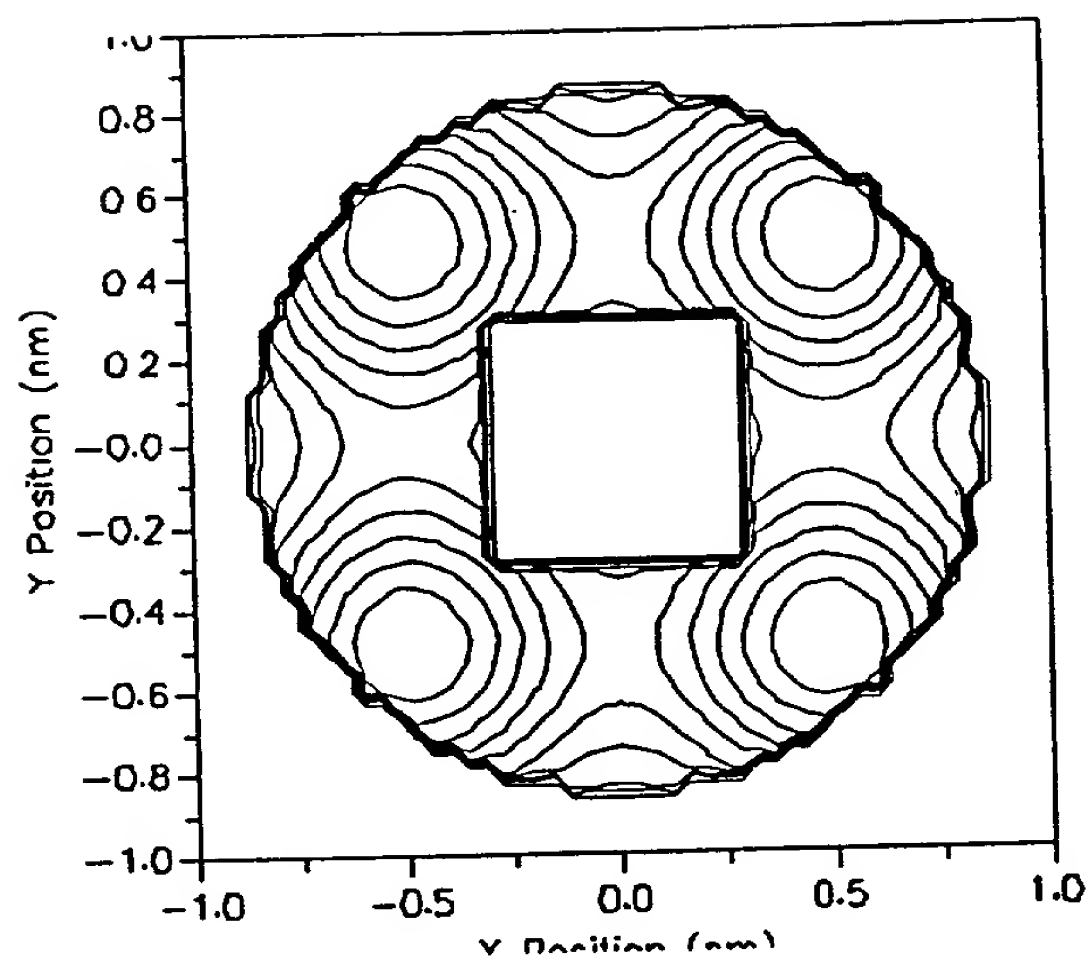


FIG.20

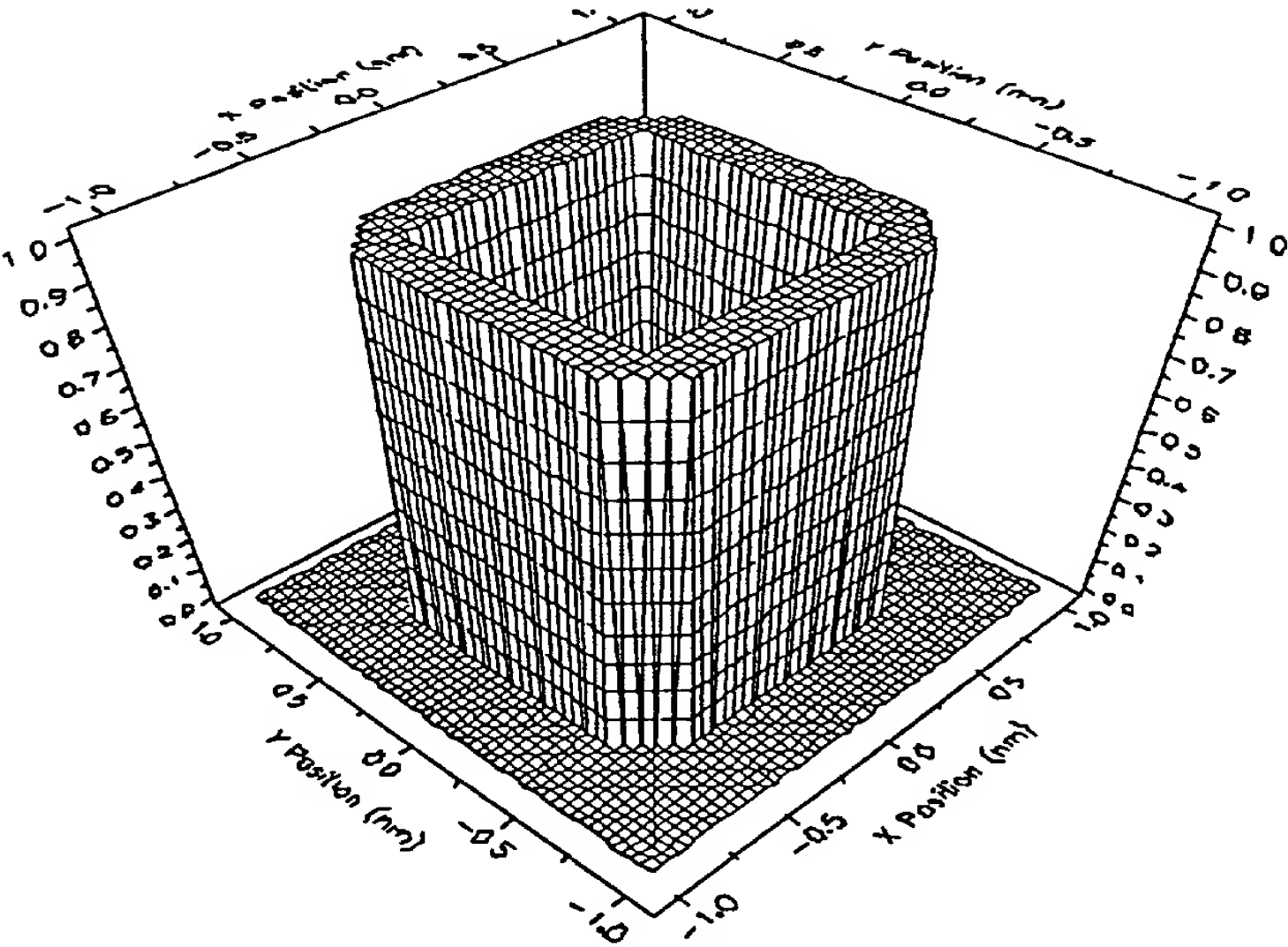


Figure 21



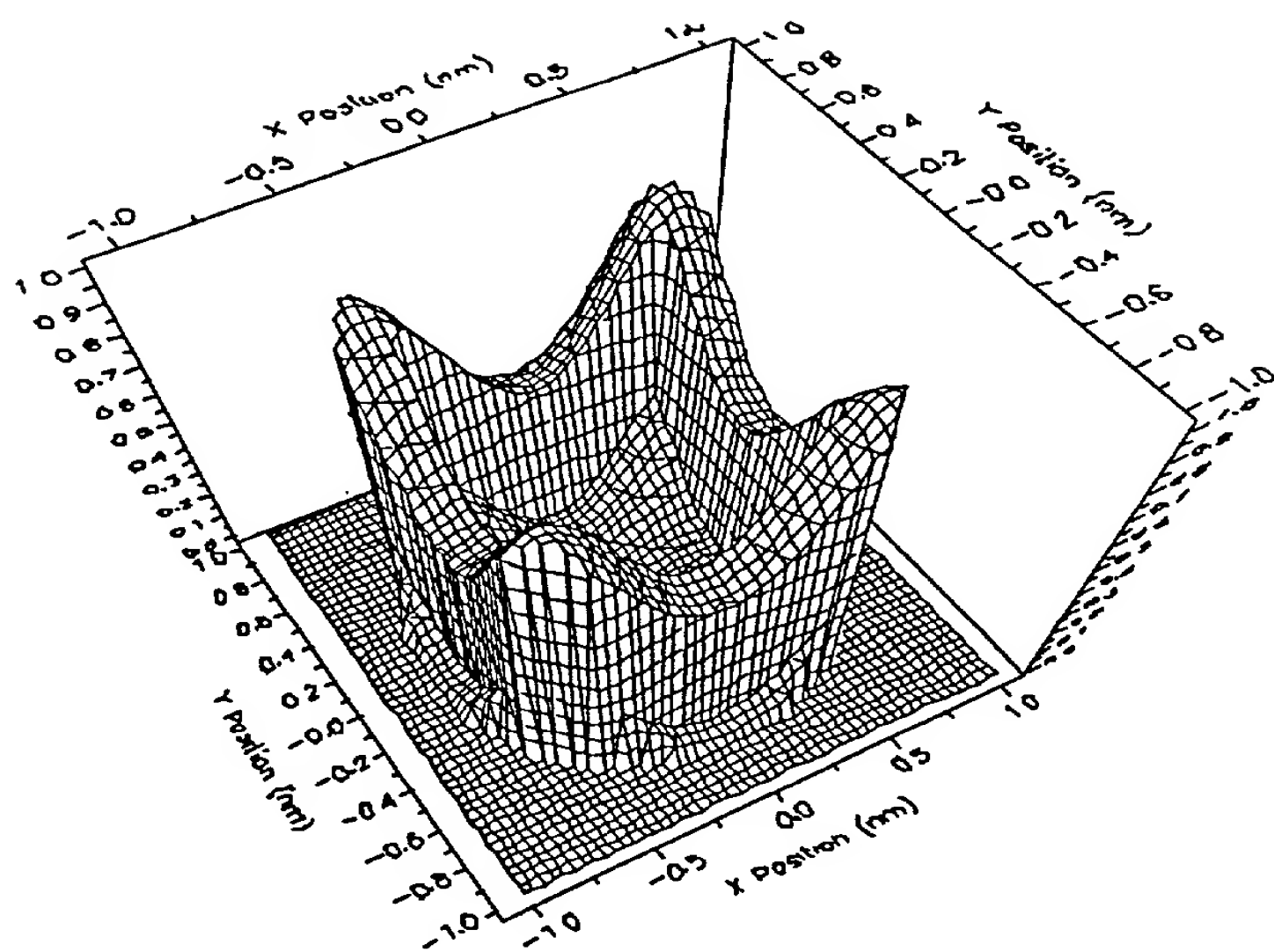
09422388-102400

Figure 22



09422398 - 102199

Figure 23



09422398-102199

Figure 24

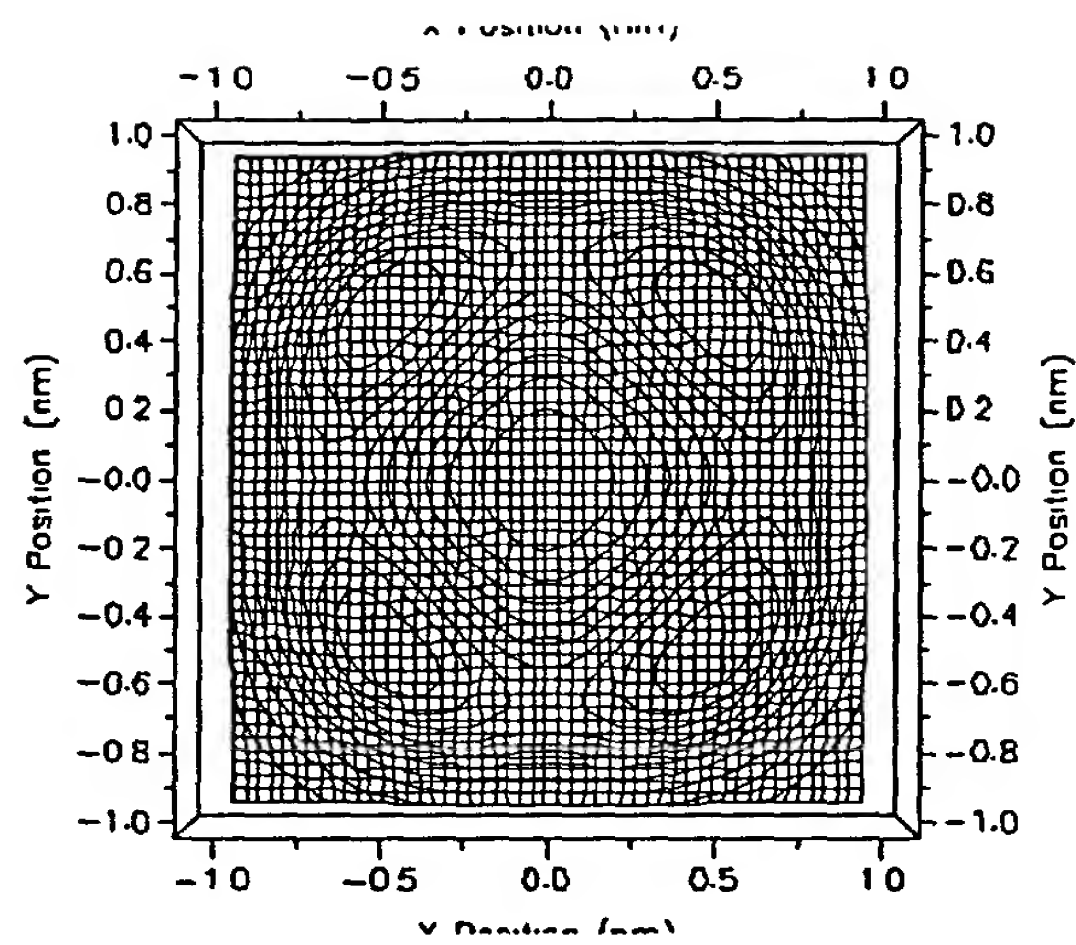
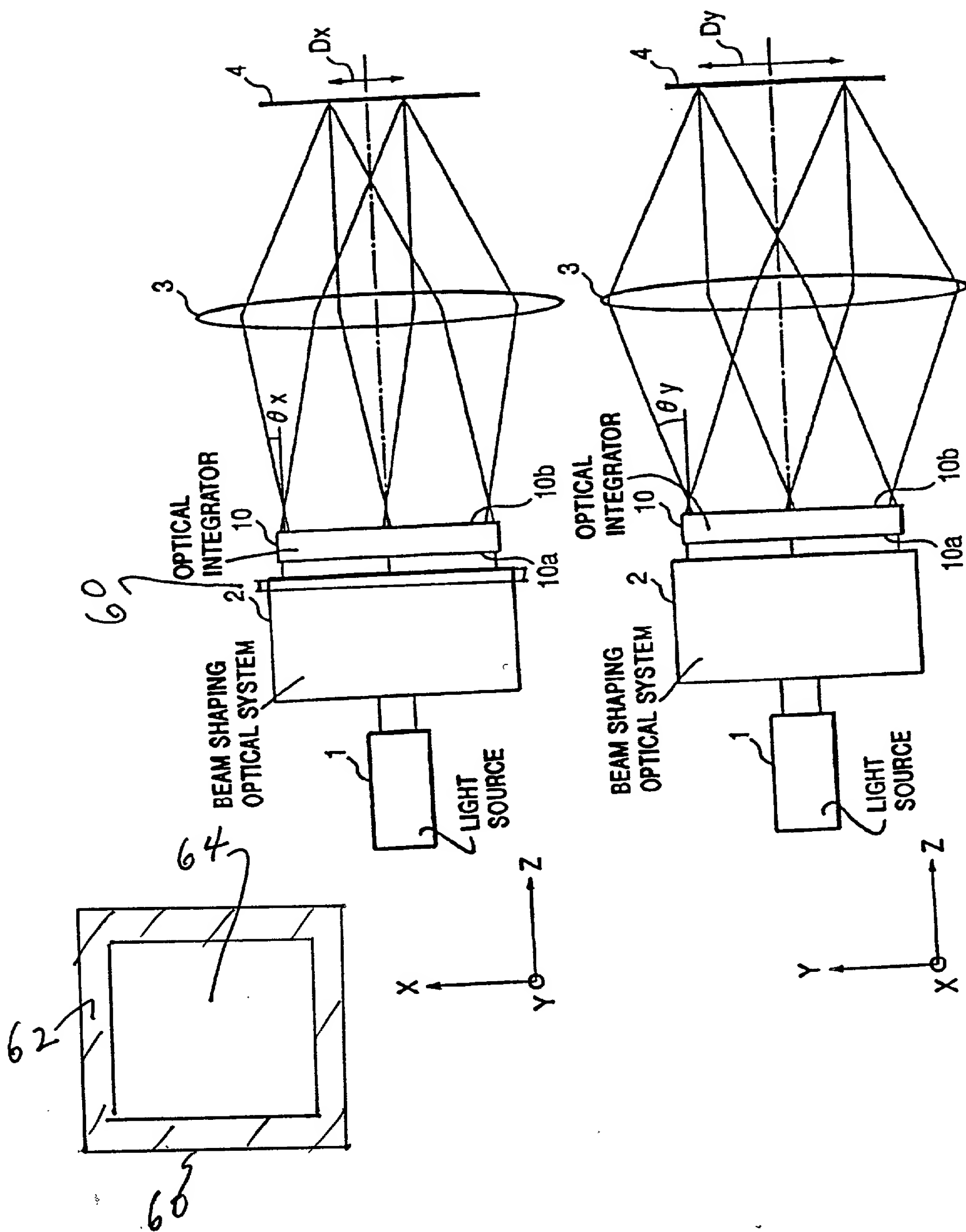


Figure 25.





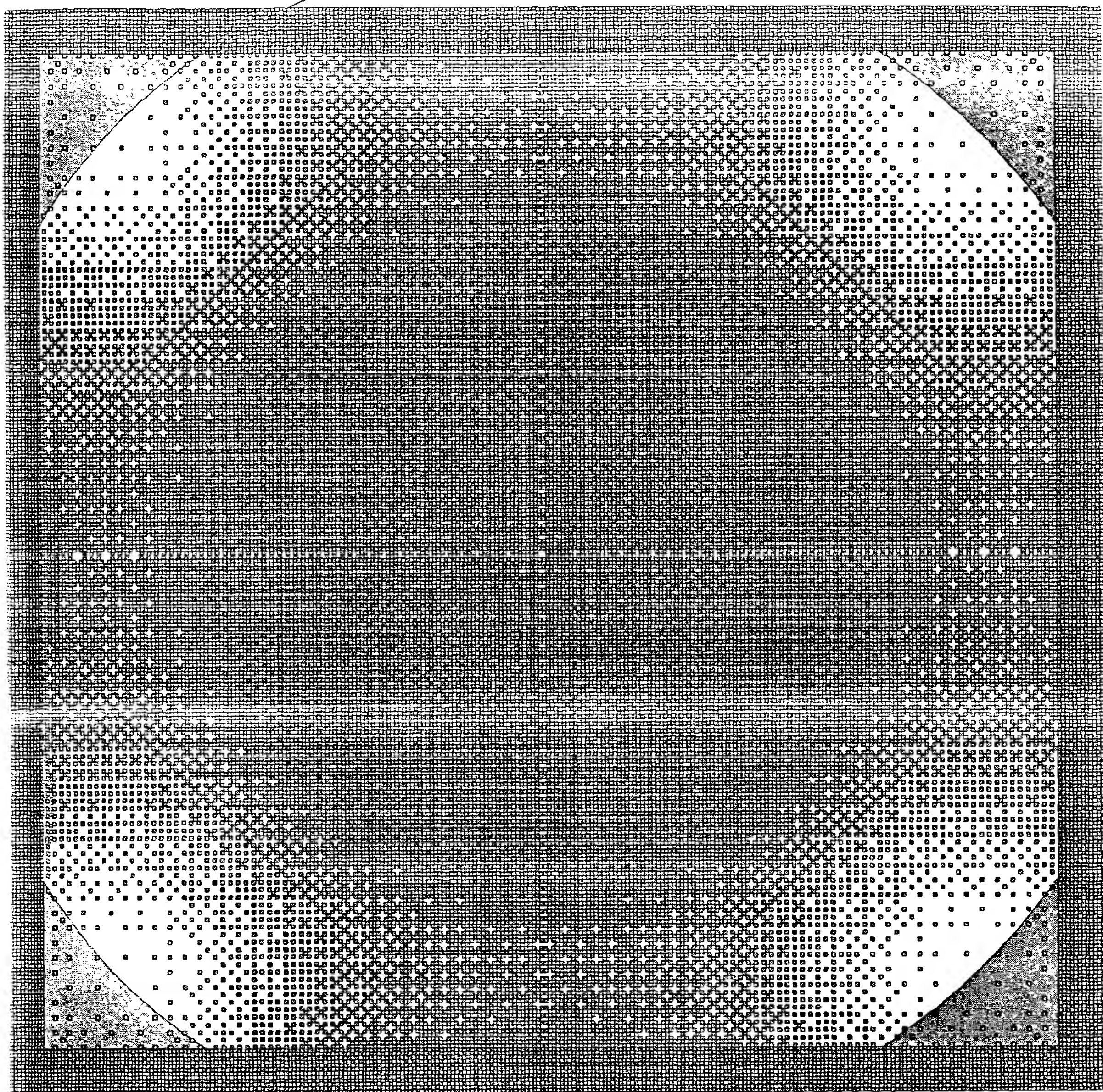


Figure 26

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PATENT APPLICATION  
(37 CFR 1.63)**

☒ Declaration Submitted with Initial Filing      OR      ☐ Declaration Submitted after Initial Filing (surcharge (37 CFR 1.16 (e)) required)

Attorney Docket Number      88405.99R077

First Named Inventor      Bruce W. Smith

**COMPLETE IF KNOWN**

Application Number      TBA

Filing Date      Herewith

Group Art Unit      Unknown

Examiner Name      Unknown

As a below named inventor, I hereby declare

My residence, post office address, and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

ILLUMINATION DEVICE FOR PROJECTION SYSTEM AND METHOD FOR FABRICATING

the specification of which      (Title of the Invention)

☒ is attached hereto

OR

☐ was filed on (MM/DD/YYYY)

as United States Application Number or PCT International

Application Number      TBA      and was amended on (MM/DD/YYYY)      (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56.

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Prior Foreign Application Number(s)	Country	Foreign Filing Date (MM/DD/YYYY)	Priority Not Claimed	Certified Copy Attached?	
				YES	NO
None			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

☐ Additional foreign application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto:

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60/105,281 60/119,780	10/22/98 02/11/99	

[Page 1 of 2]

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I hereby claim the benefit under 35 U.S.C. 120 of any United States application(s), or 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. 112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application.

U.S. Parent Application or PCT Parent Number	Parent Filing Date (MM/DD/YYYY)	Parent Patent Number (if applicable)
None		

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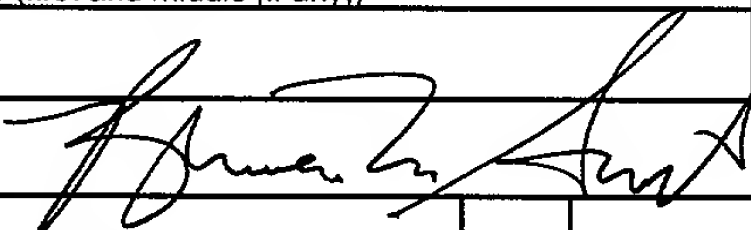
Name	Registration Number	Name	Registration Number
Thomas R. FitzGerald	26,730	Ronald S. Kareken	20,573
Lee J. Fleckenstein	36,136		

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City	Rochester	State	NY	ZIP	14614
Country	USA	Telephone	(716) 262-3640	Fax	(716) 262-4133

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Name of Sole or First Inventor:	<input type="checkbox"/> A petition has been filed for this unsigned inventor				
Given Name (first and middle [if any])			Family Name or Surname		
Bruce W.			Smith		
Inventor's Signature					Date
Residence: City	Webster	State	NY	Country	USA
Post Office Address	558 Ridge Road				
Post Office Address					
City	Webster	State	NY	ZIP	14580
				Country	USA

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